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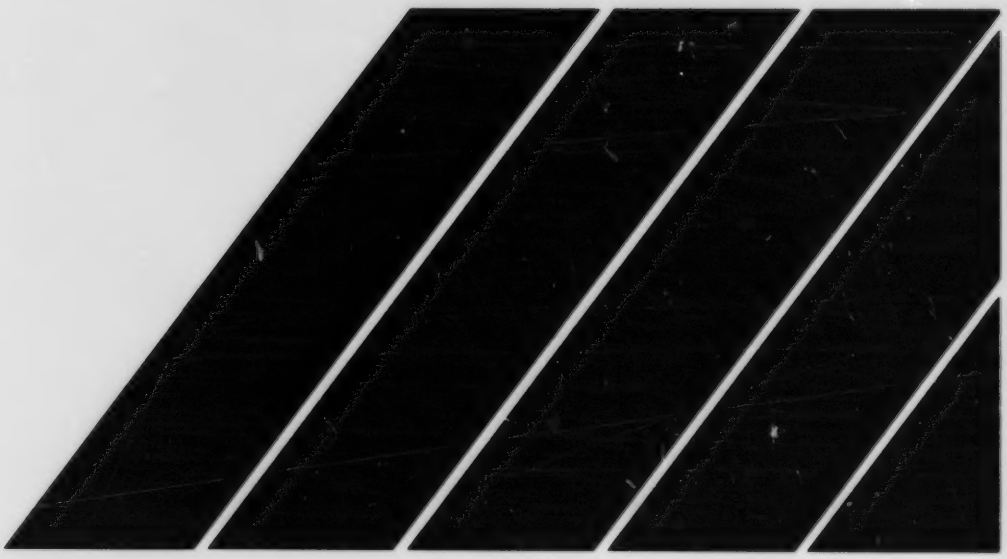
HETEROJUNCTION SILICON SOLAR CELLS, DEVELOPMENT TOWARDS INDUSTRIAL PRODUCTION



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HETEROJUNCTION SILICON SOLAR CELLS, DEVELOPMENT TOWARDS INDUSTRIAL PRODUCTION

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Energy, Mines and Resources Canada
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ABSTRACT

Single junction photovoltaic cells with a novel structure have been designed and developed as part of the present contract. These new cells are formed by depositing doped silicon (aSi) thin films on top of an oppositely doped silicon crystalline (cSi) wafer. These are classified as heterojunction aSi:cSi solar cells (HJ-cells), since aSi and cSi possess different structures and energy band gaps. The HJ-cell is developed with the ultimate objectives of achieving conversion efficiencies competitive with commercial solar cells, and reducing the cost of the wafer by increasing the active role of the top wafer.

Matching the top film with the bottom silicon wafer is crucial in the development of efficient solar cells. Experimental results show that only a fraction of the great variety of thin films is suitable. A high resistivity wafer requires a highly doped top layer, and vice versa. The best results were obtained when cells were formed by depositing a top n-doped silicon wafer at 620°C, with a phosphine/silane gas ratio of $4x10^{-3}$ onto a test-grade boron-doped silicon wafer of 5-15 Ω-cm. The I-V characteristics were V_{oc} = 0.54 volt, J_{sc} = 21 mA/cm^2, and the fill factor = 66%, resulting in a conversion efficiency of 7.4%.

The cell a underwent a satisfactory stability test. Post-deposition annealing and anti-reflection coatings with indium-tin-oxide have improved efficiency significantly, but are not yet incorporated in the final cells. Regrettably, low quality wafers such as metallurgical grade could not be obtained for testing to achieve the desired progress.

RÉSUMÉ

Le présent contrat a donné lieu à la conception et au développement d'un nouveau type d'accumulateur photovoltaïque unijonction. Ces nouveaux accumulateurs sont formés par le dépôt de couches minces de silicium dopé (aSI) sur une tranche de silicium cristallin à dopage inverse (cSi). On les appelle accumulateurs solaires hétérojonction aSi:cSi (accumulateurs HJ), puisque les structures cristallines et les bandes d'énergie du aSi et du cSi sont différentes. L'accumulateur HJ a été mis au point en vue d'obtenir éventuellement un rendement de conversion comparable à celui des accumulateurs solaires commerciaux et de réduire le coût d'achat des tranches par l'accroissement du rôle actif de la couche supérieure.

L'adaptation entre la couche supérieure et le substrat de silicium est essentielle à l'efficacité des nouveaux accumulateurs solaires. Les résultats expérimentaux démontrent que seule une minorité de la grande variété de couches minces convient pour ces dispositifs. Une tranche de résistivité élevée nécessite une couche supérieure à fort niveau de dopage et vice-versa. Les meilleurs résultats ont été obtenus avec des accumulateurs produits par le dépôt à 620 °C d'une couche de silicium à dopage n sur une tranche de qualité test de silicium dopé au bore de 5-15 Û-cm, le rapport des gaz phosphine/silane étant de 4×10^{-3}. Les caractéristiques I-V étaient V_{oc} = 0.54 volt et J_{sc} = 21 mA/cm^2, et le facteur de remplissage = 66 %, ce qui correspond à un rendement de conversion de 7.4 %.

Les tests de stabilité des accumulateurs ont donné des résultats satisfaisants. Les recours au recuit post-dépôt et à des revêtements antiréflexion indium-étain-oxyde a amélioré substantiellement l'efficacité, mais ces techniques n'ont pas encore été incorporées à la version finale des accumulateurs. Malheureusement, il a été impossible d'obtenir des tranches de faible qualité comme les semiconducteurs métallurgiques, nécessaires à la réalisation des tests permettant de passer à la phase suivante des développements.

EXECUTIVE SUMMARY

Solar energy will play an increasingly important role in energy supply in the coming years. Market research indicates that the photovoltaic industry has an excellent future. The universal and persistent concerns over environmental pollution and safety will accelerate the demand for solar power.

High price is the main reason preventing the widespread use of photovoltaic energy. This is directly related to the cost of production of cells and their efficiencies. Worldwide research and development efforts in solar cells are all directed towards the reduction of production cost and to the improvement of cell efficiencies. The work in the present contract deals with these two issues.

Single junction photovoltaic cells with a novel structure have been designed and developed as part of the present contract. These new cells are formed by depositing doped silicon (aSi) thin films on top of an oppositely doped silicon crystalline (cSi) wafer. These are classified as heterojunction aSi:cSi solar cells (HJ-cells), since aSi and cSi possess different structures and energy band gaps. The research and development of heterojunction cells at the University of Western Ontario represent a key step in our general scheme of R & D in solar cells. This hybrid cell may enable us to reduce the cost of a single junction, which can then be used to build a tandem cell to improve the efficiency.

The objectives of the investigation were : 1) to increase the efficiencies of HJ-cells; 2) to explore ways of reducing the cost of production especially by replacing the expensive single crystal wafers with cheaper, lower quality material; and 3) to address the manufacturing potential of this process.

The deposited doped silicon layers denoted as a-Si have previously been characterized by a variety of techniques. Their structures, compositions, electrical properties and optical properties have been described in an earlier report (DSS 01SR31025-4-3036). These films form the basis of our investigation. It is of particular interest to note that electrical properties such as dark and photo conductivities and carrier mobility of our doped films are superior to those of the well-known glow-discharge film, which is a silicon-hydrogen alloy. While HJ-cells with the glow-discharge alloy film as the top layer has never achieved an efficiency over 1%, the use of our films has given HJ-cells with efficiencies over 7%. The electrical and optical properties of our doped silicon film, which is produced by a low pressure chemical vapour deposition (LPCVD) system, have been analyzed extensively and found to be dependent on film structure and atomic composition. These properties are strongly related to the deposition conditions such as temperature and volume ratios of dopant and silane gases. We have also established that the deposited a-Si top layer of our HJ-cell is active in photovoltaic generation. This conclusion is based on optical absorption studies, studies of conversion efficiency as

a function of film thickness of the HJ-cell and studies of the dependence of efficiency on the $\mu\tau$ product of the film where μ is the carrier mobility and τ is the recombination lifetime.

As mentioned above we use a LPCVD system for silicon film deposition. The UWO system was designed and built in-house. One of the unique features of this system is that it can heat the substrate rapidly. For example the temperature can be raised from room temperature to 600°C in about 90 seconds. This is achieved by optical heating from two 1 kW tungsten-halogen lamps.

Silicon wafers of semiconductor grades and solar grades of various resistivity ranging from 50 ohm-cm to 0.005 ohm-cm have been acquired for the experiments. Metallurgical grade silicon wafers were sought but were not available commercially. However we were able to acquire a batch of thousand pieces of silicon wafers of no specifications but costing only 1 cent a piece to simulate lowest grade wafers. It should be noted that metallurgical grade silicon could be available if there is commercial demand for it.

The back electrode of the HJ-cell is vacuum-evaporated aluminium, which is then annealed to form an ohmic contact. Unlike other amorphous silicon solar cells, which have much lower sheet resistance and must have transparent thin film electrodes, we are able to use a metal grid as the top electrode on our HJ-cells. To protect the top aluminium electrode, to passivate the surface states and to serve as an anti-reflecting coating a silicon oxide coating was also applied. At a later stage of this project an

indium-tin-oxide (ITO) coating was also used. Some of our HJ-cells and two commercial cells were sent to the Solar Energy Research Institute (SERI), Department of Energy, U.S.A. for measurement of conversion efficiencies. These were then used as calibration standards in the measurement of subsequent cells.

The HJ-cells are formed from two materials: doped silicon film (aSi) and crystalline silicon (cSi). Proper matching the two materials is crucial for good performance of the solar cell. Several general conclusions can be drawn from these studies: a) a high resistivity wafer requires a highly doped top layer and a low resistivity wafer requires a lowly doped top layer for optimum efficiency; b) the efficiency of HJ-cells fabricated on Solar Grade wafers is only slightly smaller than those fabricated on Semiconductor Grade wafers in the same resistivity range; and c) wafers of resistivity 0.005-0.02 ohm-cm result in low efficiencies.

As mentioned a few of our HJ-cells were sent to the Solar Energy Research Institute (SERI), USA for measurements. The fabrication conditions of the top films of these cells were: deposition temperature 620°C, phosphine/silane gas ratio 4×10^{-3}, and time of deposition 60 minutes. The bottom silicon wafer was a test grade wafer of 5-15 Ωcm resistance. The top aluminum electrode covered about 8% of the area of the cell. The size of the cells was about 1 cm x 1 cm. They also had a silicon oxide protective coating which also served as anti-reflective coatings. The oxide coating resulted in increase in cell performance by more

than 25% particularly in the current output. The typical I-V characteristics of these cells are V_{oc} = 0.54 volts, Jsc = 21 mA/cm^2 , fill factor = 66% , and conversion efficiency 7.4% . This result should be compared with the result for a commercial terrestrial solar cell from TPK Solar System Inc., which was also measured at the same time by SERI. The efficiency of the TPK cell was 5.5% with IV characteristics Voc = 0.47 volts, Jsc = 24 mA/cm^2 , and fill factor = 49%. It is very encouraging that the process we have developed at U.W.O. can be competitive with conventional industrial processes.

As mentioned earlier, metallurgical grade silicon wafers were not available in the market and so in place of them we used low resistivity wafers (0.005-0.02 ohm-cm) to simulate these experiments. So far efficiencies of the HJ-cells on this set of wafers have not gone over 1%. However when the 1 cent wafer and therefore presumably the lowest grade wafer was used we could achieve an efficiency over 5%. A reliable supply of low cost, low grade silicon wafers with their specifications is needed before we can assess the processes realistically with respect to the cost reduction aspects and possibilities.

Post-deposition treatment of HJ-cells by annealing greatly enhances the IV characteristics and the efficiencies. General improvement of 50% to 200% in efficiencies has been realised. Results of the post-deposition treatment indicates that the efficiencies of HJ-cells could reach over 10%, which is

extremely encouraging and promising. There is an analogous study carried at Carleton University with high grade silicon wafers, which reports cell voltage (0.67 V) higher than a conventional Si cell (0.55 V).

Another set of experiments, which has given encouraging results is the use of indium-tin-oxide (ITO) as an anti-reflection coating. With such an coating the efficiency of the HJ-cell increased by about 100% compared to that without the coating. The physical properties that make ITO attractive are that it is transparent to the solar spectrum, it is electrically conductive, and it is an n^+-doped material.

With the help of Dr.Raye Thomas of Astropower Canada Ltd. it is assessed that our process is comparable in capital and labour cost with the traditional process in manufacturing solar cells. The advantages of an HJ-cell are that both cell voltage and cell efficiency can be higher than in a conventional cell. The cost of the silicon wafer substrate could be reduced in the production of an HJ-cell by the use of low grade and thus low cost materials such as metallurgical grade silicon since most of the photovoltaic action occurs in the deposited aSi layer. Our work suggests that this can be successfully developed and that the price of the HJ-cell will be cheaper than that of a conventional Si cell. Moreover, by building another thin film cell on top of the HJ-cell in a tandem cell configuration, the open circuit voltage and therefore the overall efficiency can be further improved.

1. INTRODUCTION

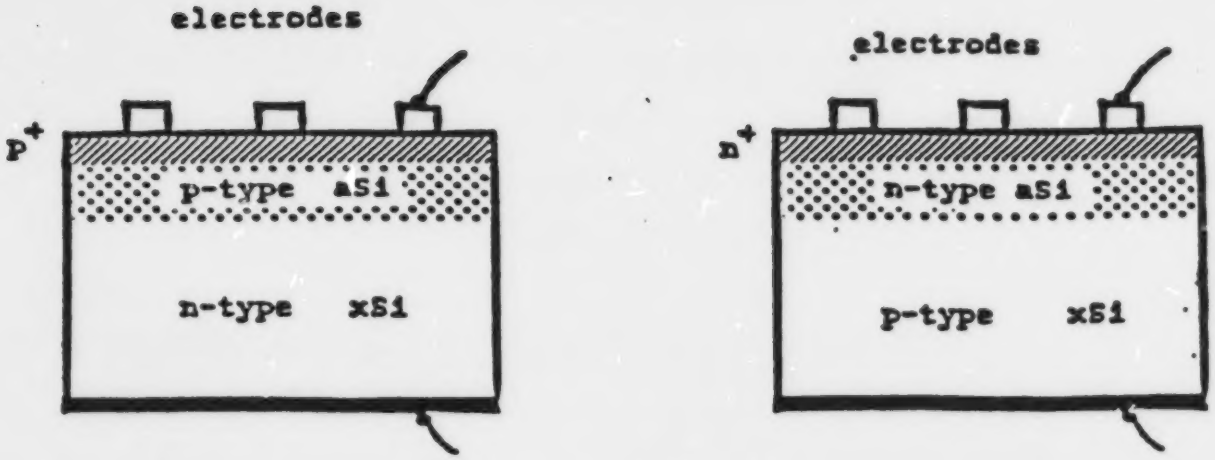
Solar energy will play an increasingly important role in energy supply in the coming years and market research (1.1) indicates that the photovoltaic industry has an excellent future. The price of photovoltaic energy has dropped to about to one tenth of its cost since the oil embargo in the seventies. However the unexpected softening of oil prices and the oversupply of natural gas in North America has prevented the photovoltaic industry from penetrating the market. But oil and natural gas are nonrenewable resources and their prices will be going up, while that of photovoltaic energy will come down from about $4/Wp in 1990 to a projected $2/Wp in 2000. Further, the universal and persistent concerns over environmental pollution and safety make photovoltaic energy politically appealing as well.

Currently there are three major types of photovoltaic systems all of which use silicon as the principal material for photovoltaic energy conversion. These are classified as single crystal, polycrystalline, and amorphous silicon-based modules. The single crystal and polycrystalline cells, which are based on bulk material, are mainly used in direct sunlight environments while the amorphous cells, which are thin film devices, are successfully used for consumer products indoors.

When photovoltaic energy eventually contributes to a significant percentage of global energy usage the solar cells that would dominate the market will be the thin film cells. The present day thin film amorphous silicon cell (in fact silicon-hydrogen alloy cell), even though it suffers from low efficiency and instability problems has the advantage of large area continuous processing and use of automation and therefore has potentials for low cost. Much research and development are needed to explore these advantages. On the other hand the crystalline solar cell because of its high efficiency and stability and therefore reliability still plays the dominant role in outdoor applications. A recent theoretical study (1.2) claims that with proper light trapping a single junction solar cell could achieve a conversion efficiency of 38% and that a working cell could reach an efficiency of 30%. So the research and development of the crystalline cell cannot be ignored and needs to be pursued.

The work performed under the present contract reflects and follows the above trends in worldwide R and D in photovoltaics. The work reported here represents a crucial step in our overall plan in R and D in solar cells. The heterojunction aSi:cSi solar cell studied at the University of Western Ontario is neither conventional bulk material solar cells nor the present day amorphous silicon thin film cells. It is a hybrid heterojunction cell: a doped thin film deposited on top of an oppositely doped silicon bulk material as shown in Figure 1. There are several

FIG 1 HETEROJUNCTION SOLAR CELLS



(n,p) -aSi: amorphous silicon or microcrystalline silicon in a matrix of amorphous silicon. These materials are produced from our own LPCVD system.

(p,n)-xSi: either single crystalline silicon wafers or lower grade crystalline material like crystalline ribbons of Si, or polycrystals.

Electrodes & AR coating: electrodes in the form of metal fingers seem to be adequate for our material.

advantages and potentials for these new cells. These are outlined briefly as follows:

1) Our heterojunction cell has a configuration similar to that of a conventional p-n junction. The main difference is that the top layer in the conventional cell is a diffused layer while ours is a deposited layer. The diffusion method creates a 'dead' layer which reduces the solar cell efficiency. The deposition method allows a possible way to avoid the 'dead' layer and consequently improves efficiency.

2) Our deposited silicon thin film layer can be variously doped. The structural properties of the film can be controlled to be amorphous, microcrystalline or polycrystalline structures with different electronic and optical properties so that some of these layers may be chosen to match the quality (property) of the bottom bulk silicon wafer to obtain cells with optimum efficiency. By proper design and matching one can ensure that most of the photovoltaic action takes place in the top deposited layer of the heterojunction solar cell so that low quality and therefore low cost silicon wafers can be used as substrate to reduce the overall cost of solar cells.

3) This heterojunction cell with a top deposited thin silicon layer would provide the Canadian industry a stepping stone in the production of truly thin film cells, which are made entirely of thin films, where the future of photovoltaic industry probably lie.

4) By stacking a thin film cell of the type mentioned in

step 3) on top of the HJ-cell developed in steps 1) and 2), a tandem cell, which in principle has better overall efficiency and higher output voltage than the component cells, can be developed.

The work reported here has addressed R and D related to the above the first two steps. The next section describes the objectives of the contract, followed by the detailed report.

2. OBJECTIVES

The 1984/85 program supported by EMR resulted in producing efficient HJ-cells. This led to the present program, a study towards industrial production of the HJ-cells. The main objective of the program is to compare the competitiveness of the HJ-cells with the crystalline silicon solar cells fabricated in the conventional way. The program therefore consists of developmental steps to increase the efficiency of the product, to reduce the cost of production, and in parallel with the technical program, to study of the manufacturing potential:

(a) To increase the efficiency of HJ-cells: Several technical and scientific aspects are pursued to increase the efficiency. As an example, in the 1985 HJ-cells, the achieved efficiency 9-10 % was based on the " active area " of the exposed solar cell. While the area of the cell was 0.5cm x 0.5cm , only about 55 % of the area was active. As a commercial product, the effective efficiency is reduced by approximately half. In this program, we aim at fabricating a HJ-cell as a competitive

industrial product.

(b) To lower the cost of production: The fabrication procedure is streamlined to cut down non-essential processes. Alternate procedures are compared for the cost of labour and degree of control needed. The choice of materials for electrodes, and for surface protection are considered. One major cost of the solar cell is the single crystal wafer. We hope to replace the expensive good quality silicon wafers by a much cheaper lower grade material.

(c) To study the manufacturing potential: This part of the study is to be carried out in conjunction with an industrial partner: Dr. R. Thomas, Astropower, and Mr. T. Dielschneider, of the Small Business Program of the U.W.O. Business School.

The STATEMENT OF TASKS as stated in the original contract is included as Appendix 2 for reference. We have achieved all the main tasks under the contract. Experiment with metallurgical grade silicon could not be performed as it was not available commercially. It should be pointed out that metallurgical grade silicon would be available if there is an industrial demand for it. A marketing report was started but not completed by Mr. Dielschneider, a former student of School of Business Adminstration, U.W.O., who left the School in the middle of the contract program. Fortunately this loss is recovered with the excellent report prepared by Dr. Thomas entitled " Technology and Economics of Heterojunction Amorphous Silicon Solar Cell Production".

3. BACKGROUND ON THE DOPED SILICON THIN FILMS AND THE HETEROJUNCTION CELLS

3.1 Doped Silicon Thin Films

We have studied the production and the properties of doped silicon thin films, which is the top layer of the heterojunction cell. They have been reported in several journal papers (3.1.1-4) and in our report to DSS, File No. 0ISR31025-4-3036 entitled " Fabrication of Heterojunction aSi:xSi Solar Cells Out of New Doped Material Produced in our Laboratory " by Tong, Wong and John (3.1.5). In that report we discussed thin film production by a low pressure chemical vapour deposition (LPCVD) system, mechanism and rate of film growth, structural analysis of the LPCVD films, dopant concentration measurements and physical properties including optical properties, dark and photo-conductivities, Hall mobilities and thermo-electric power measurements.

In this section we present only a brief summary of the analysis and the measured properties. (Some details are provided in Appendices 3.1.1-2). X-ray diffraction, laser Raman spectroscopy and transmission electron microscopy were used to monitor the first appearance of crystallinity. We have mapped the appearance of crystallinity as functions of the dopant gas to silane ratio (R) and the substrate-temperature (Ts) as shown in Figure 3.1.1 and Figure 3.1.2. There are typically two zones in these maps: amorphous and microcrystalline. In the case of boron doped films

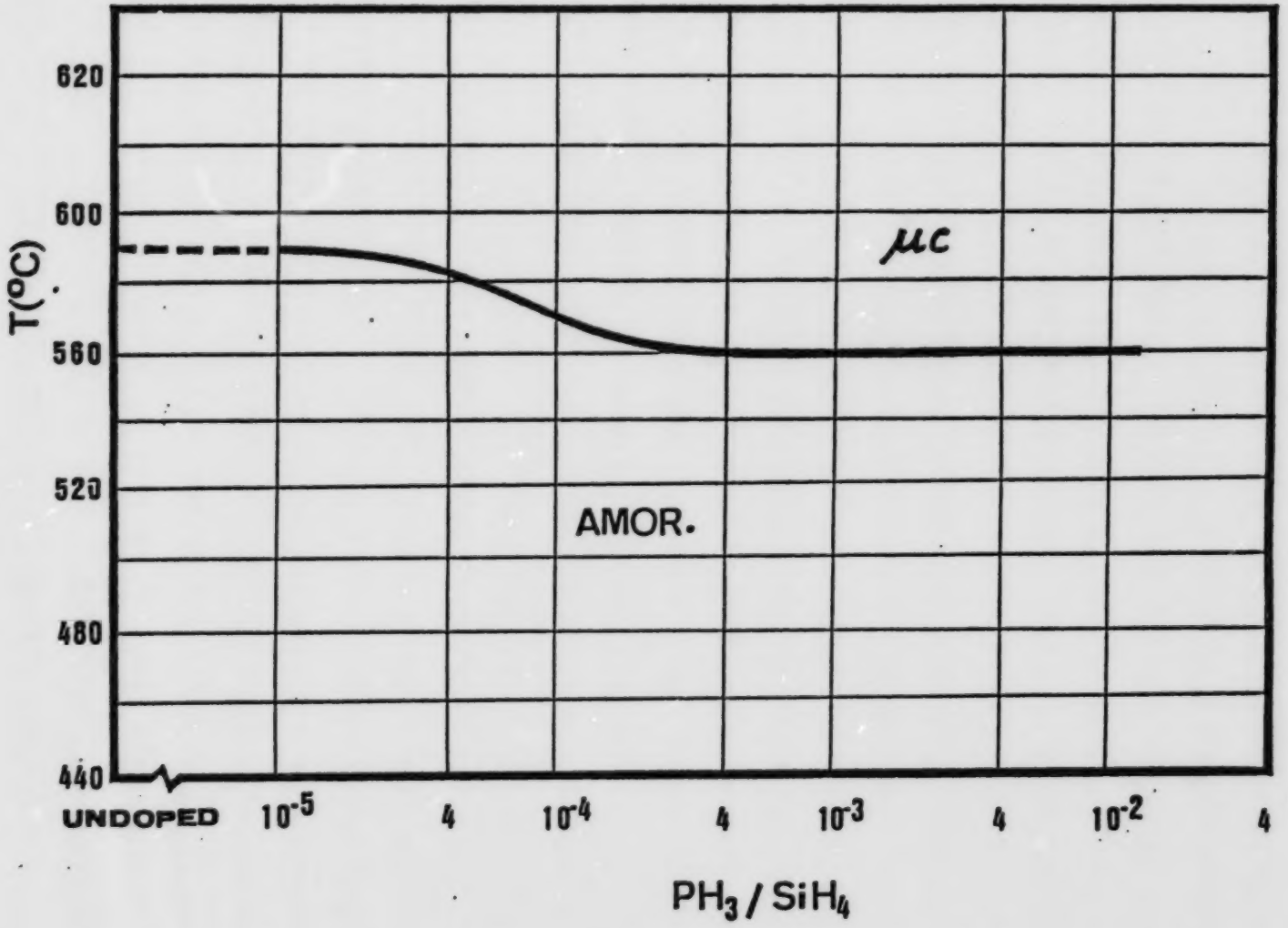


Figure 3.1.1 Zones of Different Phosphorus-Doped aSi Material: Amorphous (AMOR.) and Microcrystalline (μC)

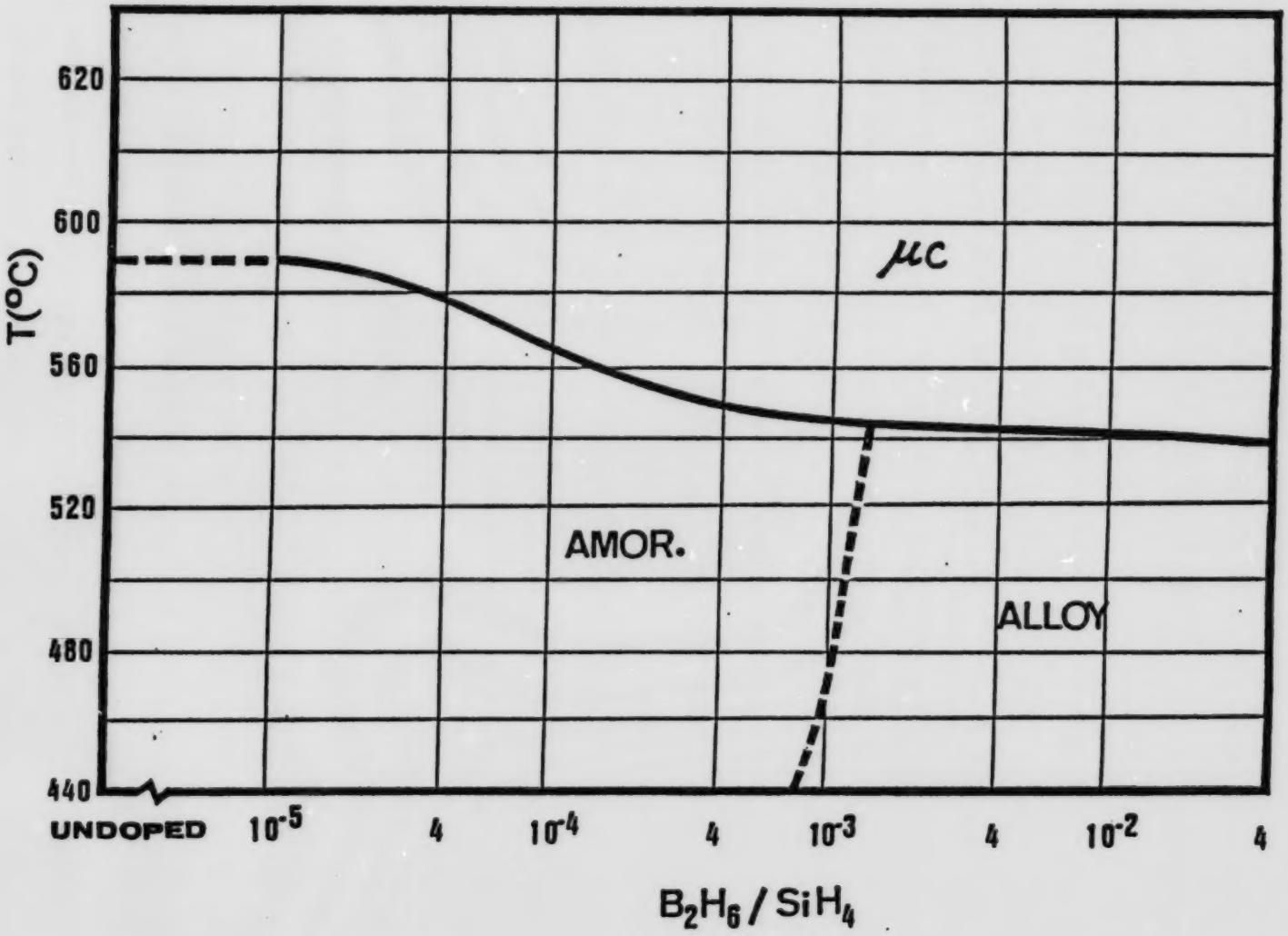


Figure 3.1.2 Zones of Different Boron-Doped aSi material: Amorphous (AMOR.), Alloy (ALLOY), and Microcrystalline (μC)

there is a new zone classified as "alloy" where the structure is amorphous and when the boron concentration is more than 5 atom per cent.

Dopant concentrations were measured by secondary ion mass spectrometry (SIMS). The results as functions of R and Ts are shown in the 3-dimensional maps in Appendix 3.1.1 and 3.1.2. Electrical properties are most relevant to the studies. Tables 3.1.1 and 3.1.2 summarize our results obtained and are compared with results from some of the major laboratories in the world. These results show that LPCVD provides films with better electrical conductivities and therefore better quality films in both the amorphous or microcrystalline states.

For thin films dopant concentrations alone do not determine the value of conductivity unlike the case of the single crystal. The temperature of the deposition is vitally important as shown in Figure 3.1.3 and Figure 3.1.4. It is seen that in the temperature range studied the deposition temperature affects the structure of the films; and it indicates the higher the temperature the better the structural order. When deposition temperature is high enough crystallinity appears, as studied by X-ray diffraction, laser Raman spectroscopy and transmission electron microscopy. The better order also results in a higher efficiency of doping with the same concentration of dopants. The better the structure the better the electrical properties of these doped films. These are the basic factors governing the development of our H-J cells.

TABLE 3.1.1

Dark Conductivity of Doped a-Silicon Films (in $\Omega^{-1}cm_{-1}$)

Research Group	Method of preparation	BORON DOPED		PHOSPHORUS DOPED	
		Gas Ratio	σ_{RT} $(\Omega.cm)^{-1}$	Gas Ratio	σ_{RT} $(\Omega.cm)^{-1}$
D.E. Carlson[1]	G. D.	1.3×10^{-2}	2.2×10^{-3}	2×10^{-2}	1×10^{-2}
W.E. Spear[2]	G. D.	1×10^{-3} 1×10^{-2}	1×10^{-5} 1×10^{-4}	1×10^{-3} 1×10^{-2}	5×10^{-2} 1×10^{-2}
M. Hirose[3]	G. D.	1×10^{-3} 1×10^{-2}	1×10^{-4} 1×10^{-3}	1×10^{-3} 1×10^{-2}	1×10^{-7} 1×10^{-2}
D. Kaplan[4] et al (600°C)	C.V.D.	1×10^{-3} 5×10^{-3}	8×10^{-2} 8×10^{-2}	1×10^{-3} 1×10^{-2}	6×10^{-2} 1×10^{-1}
U. W. O.	LPVCD	1×10^{-3} 1×10^{-2}	2×10^{-1} 1×10^{-1}	1×10^{-3} 4×10^{-3}	1×10^{-2} 40

(1) D.E. Carlson: Philoso. Mag. B45, 1, (1982) 51-68.

(2) W.E. Spear, P.G. LeComber: Ibid B33, 6, (1976) 935-949.

(3) M. Hirose: J. De Physique 42, 10, (1981) C4-705.

(4) J. Magarino, D. Kaplan, A. Friderich: Philos. Mag. B45, 3, (1982) 285-306.

TABLE 3.1.2

Dark Conductivity of Doped Microcrystal Silicon Films (in $\Omega^{-1}cm^{-1}$)

Research Group	Method of preparation	BORON DOPED		PHOSPHORUS DOPED	
		Gas Ratio R	σ_{RT} $(\Omega.cm)^{-1}$	Gas Ratio R	σ_{RT} $(\Omega.cm)^{-1}$
T. Hamasaki[1] et al	G. D. (300°C)	1×10^{-2}	1×10^{-1}		
Y. Mishima[2] et al	G. D. (200°C-300°C) CVD * (1050°C)			1.9×10^{-3} 5.7×10^{-3}	6.2×10^{-4} 500
W.E. Spear[3] et al	G. D. (280°C)	1×10^{-3} 1×10^{-2}	1×10^{-4} 2×10^{-4}	1×10^{-3} 1×10^{-2}	2 20
A. Matsuda[4] et al	G. D.	1×10^{-3} 1×10^{-2}	5×10^{-5} 3×10^{-2}		
S. Hasegawa[5] et al	CVD * (1050°C)	1×10^{-3} 1×10^{-2}	20 40	1×10^{-3} 1×10^{-2}	110 80
U. W. O.	LPCVD (620°C)	1×10^{-3} 1×10^{-2}	93 83	1×10^{-3} 4×10^{-3}	26 179

(1) Jap. J. Appl. Phys. 20, (1981), L84.

(2) Ibid 20 (1981), L121.

(3) J. De Physique, Colloque C4 Tome 42 (1981) C4257

(4) Jap. J. Appl. Phys. 20, (1981), L183

(5) J. Appl. Phys. 55(2) (1984) 542.

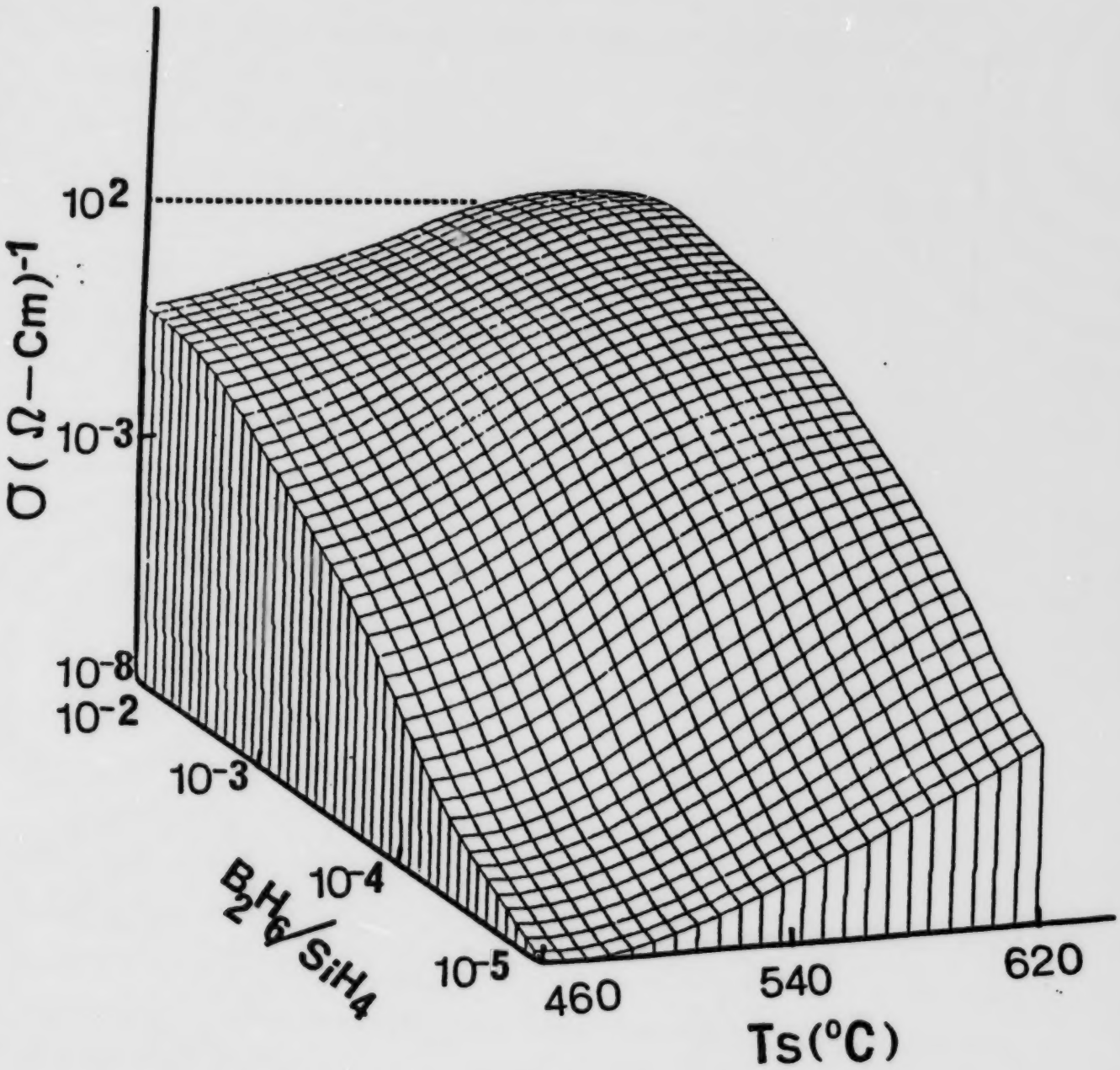


Figure 3.1.3 Room Temperature Dark Conductivity of Boron-Doped aSi Material as a Function of R and Ts

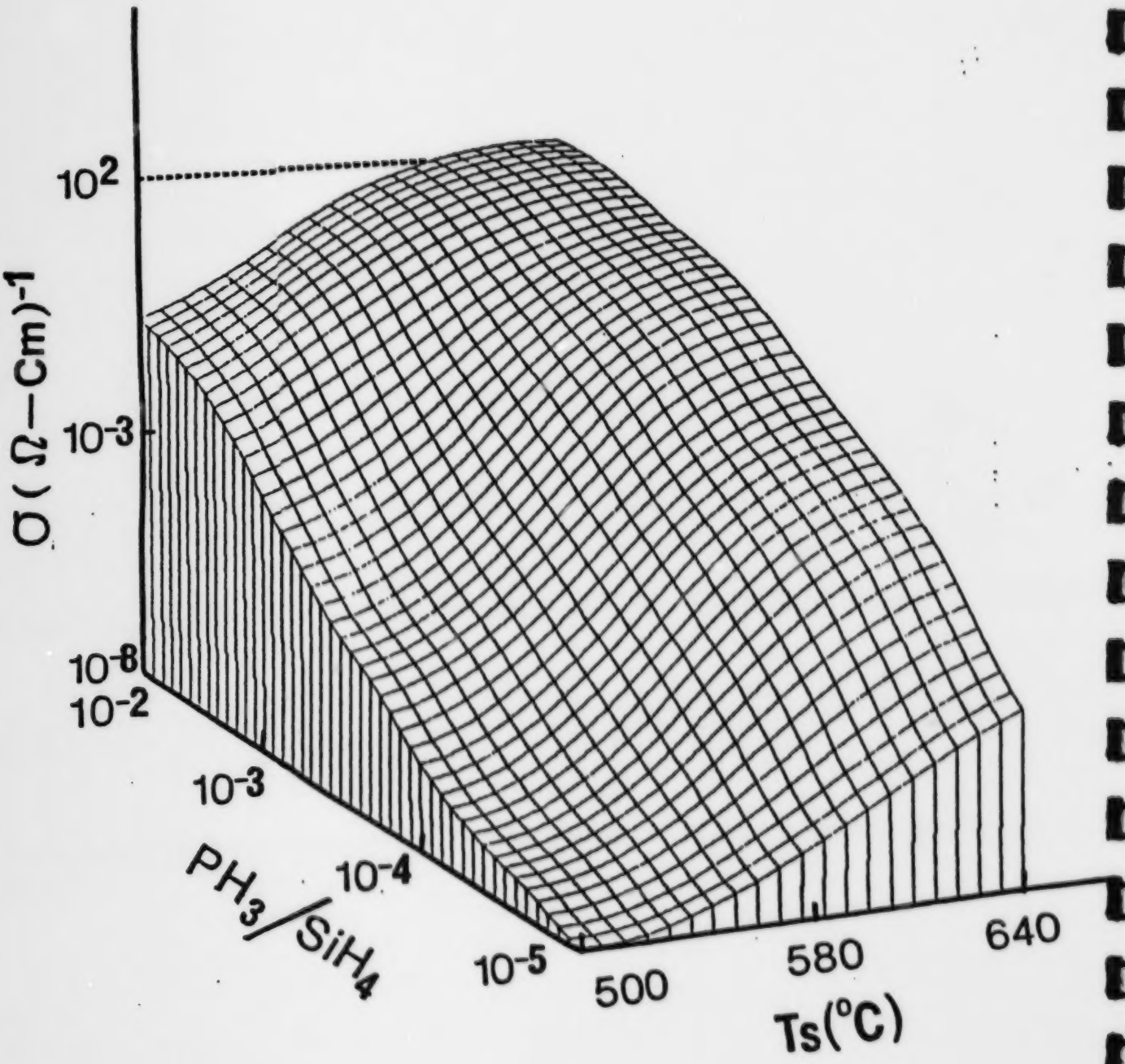


Figure 3.1.4 Room Temperature Dark Conductivity of Phosphorus-Doped aSi material as a Function of R and Ts

3.2 The Heterojunction Cells Prior to the Present Contract

The HJ-cells are formed from two materials of different energy bandgaps: doped amorphous or microcrystalline silicon film (aSi) and crystalline silicon (cSi). Single crystalline silicon has an energy bandgap of 1.12 eV while LPCVD grown silicon has energy bandgaps varying from 1.2 -1.6 eV dependent on the structure, type of dopant and dopant concentration, and glow discharge grown silicon-hydrogen alloy has an energy bandgap of 1.8 eV (3.1.1-2, 3.2.1-2). The quality of the doped silicon film by glow discharge is poor (see Table 3.1.1 and Table 3.1.2). Indeed the glow discharge method has never produced HJ-cells with conversion efficiency over 1%. In contrast, our LPCVD method had produced HJ-cells reaching 10% efficiency over the active area before the present contract started. This was reported in a paper (3.1.2) and in the previous contract report (DSS OISR31025-4-3036). (3.1.5).

From optical absorption studies of thin films and the study of conversion efficiency as a function of film thickness of the heterojunction cell, it was observed that the top doped layer took an active part in the absorption of the incident light, in the generation of electron-hole pairs, and their transport across the film. Further support of the above conclusion comes from the measurement which shows that the solar cell efficiency depends on the product $\mu\tau$ where μ is the carrier mobility and τ is the recombination lifetime for the film. The results are shown in Figure 3.2.

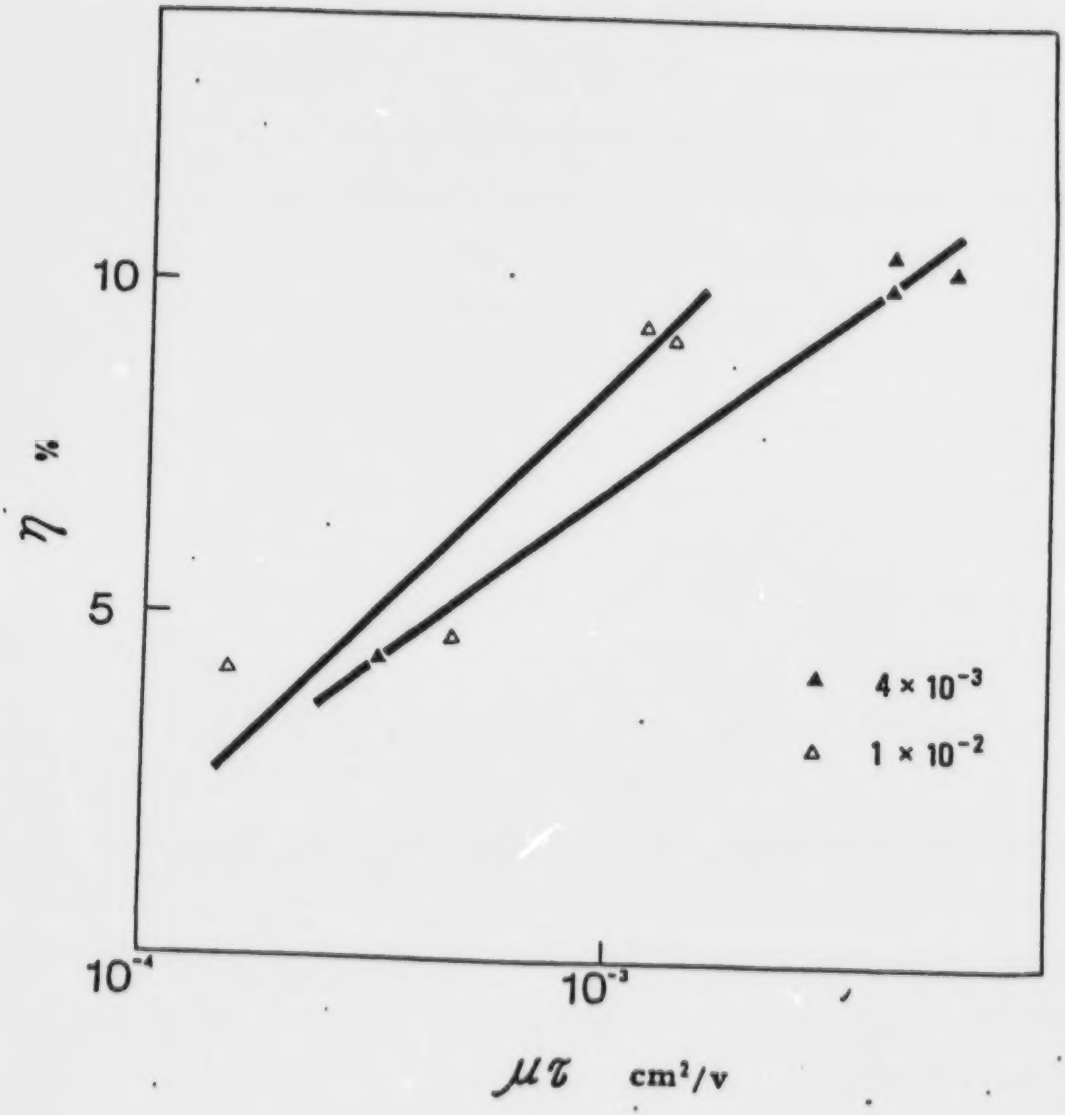


Figure 3.2 Correlation between Solar Cell Efficiency η and $\mu\tau$ Product of Thin Films Deposited on Glass

The present contract was based on the belief that if we could increase the role of the top deposited layer by varying the conditions of deposition, such as dopant concentration, deposition temperature, film thickness, post-deposition treatment etc., we might reduce the role of the substrate. Lower quality silicon could be used thereby to reduce the cost of the solar cell.

4. METHOD

4.1 Film Deposition System

A low pressure chemical vapour deposition (LPCVD) system was used in this contract. LPCVD is the most popular method for film deposition. The UWO system was custom-designed and built in our laboratory and has special appeal for research purposes and as a low cost system. The schematic diagram of the reactor is depicted in Figure 4.1 . One of the unique features of this system is the rapid heating of the substrate. For example the temperature can be raised from room temperature to 600°C in about 90 seconds. This is achieved by two 1 kW tungsten-halogen lamps. It is also important to point out that while our system is simple in design and construction it has incorporated all the basic functions of other commercial LPCVD system in popular use.

4.2 Silicon Wafer Substrate

The price of a silicon wafer differs greatly according to the purity of the material. The intrinsic cost of the purification

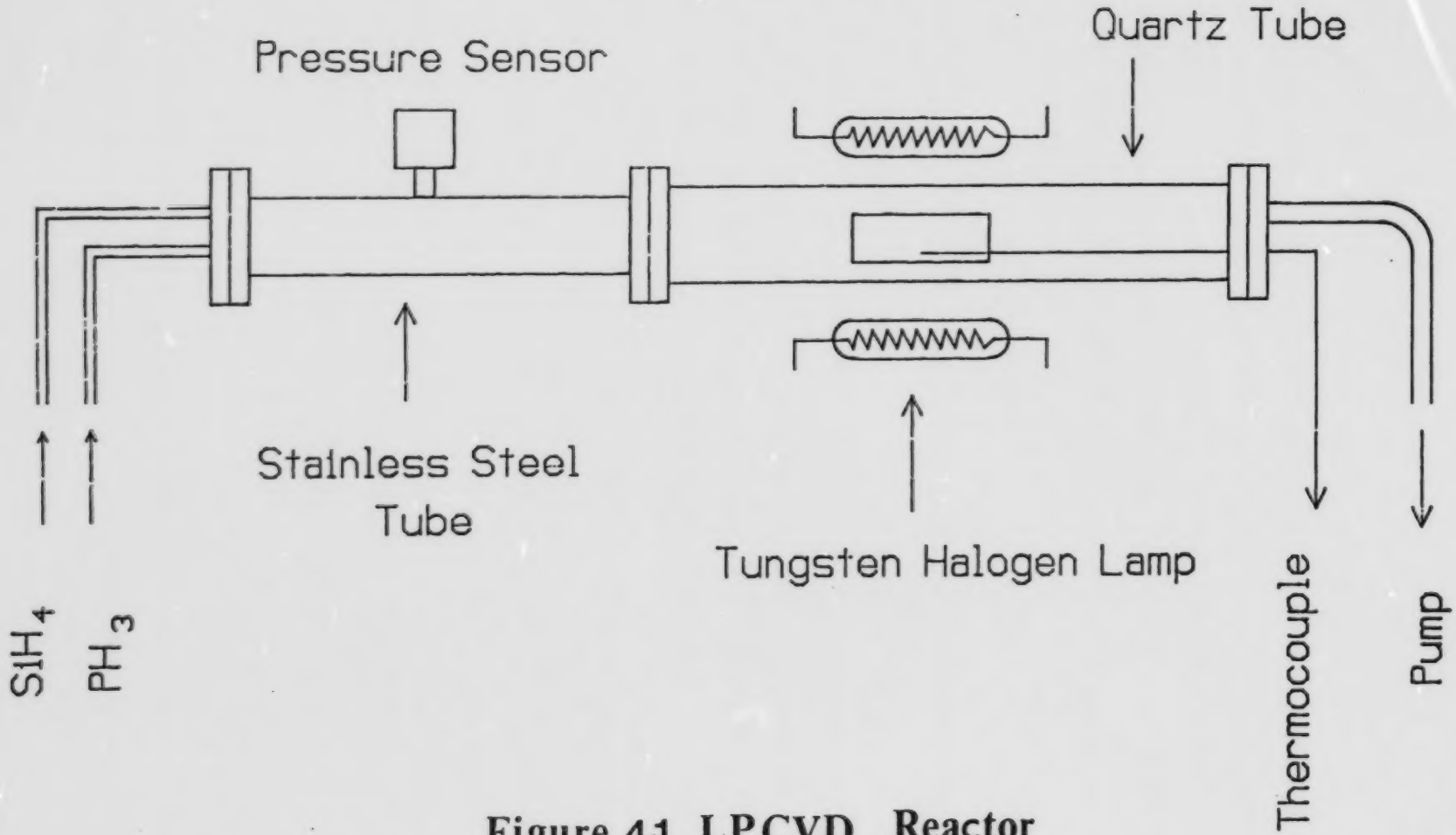


Figure 4.1 LPCVD Reactor

process increases exponentially with the demand for purity. The active contribution of the top aSi layer in photovoltaic generation in our HJ-cell affords to the possibility of reducing the purity requirement in the silicon wafer used as the substrate. For this purpose, we have collected a variety of commercially available wafers. A list of wafers now in our laboratory is shown in Appendix 4.2 .

It is not easy to buy small amounts of wafers direct from manufacturers. Other than lot 47, which we obtained from Monsanto as reject test wafers, most others were purchased from the silicon market such as the Aurel Company, which has gone out of business recently. The wafers are labelled as Test, Prime, and Solar grades. The unit price of Test and Prime wafers is in the range of US$ 5-7 and the unit price for solar grade wafers is US$ 1.5. Semiconductor grade wafers with high dopant concentration is more expensive (for example, lot 5 and lot 80-2), because dopant impurity is usually introduced after purification. For solar grade wafers, resistivity can be used as a guiding index of purity of the material. The price of all solar grade material is the same. We can assume the true price of the solar grade wafers is lower than this amount, US$ 1.50 per wafer.

Wafers obtained from a second hand source naturally vary in quality. In the course of our studies, we did encounter irregularity. This is especially noticeable in solar grade

material. This affects our processing procedures , but the final product of HJ-cells is about the same. This is one indication that our original idea is correct.

Metallurgical grade silicon could not be acquired for our experiments. It is not produced commercially in wafer form. Metallurgical grade silicon in powder form is produced in the Province of Quebec. We believe that metallurgical grade silicon wafers would be available if there is an industrial demand for it. We instead acquired one thousand pieces of silicon wafers of no specifications for 1 cent a piece as substitutes.

4.3 Wafer cleaning

In preparing wafers for deposition, we found that the cleaning procedure needed depends on the characteristics of the wafer. Our experience with the Monsanto Test Grade wafers of resistivity 5-15 ohm-cm is that a minimum amount of cleaning namely degreasing and rinsing in deionized water and isopropanol, is sufficient to produce good solar cells.

For silicon wafers that are heavily doped with resistivity 0.005-0.02 ohm-cm, a more elaborate cleaning procedure is required. The presence of small amount of mobile impurity ions strongly affect the performance of such solar cells, even though the wafers are classified as Test Grade. The cleaning method we used is a modified version of the procedures established at the RCA Laboratory (Appendix 4.3). Wafers that are classified as

Solar Grade, are often handled by the dealers less carefully. We find it safer to clean the solar grade wafers by the modified method, and for low resistivity wafers, the efficiency is increased quite significantly.

Our conclusion is that for high resistivity wafers, a simplified version of cleaning procedure is sufficient, but for solar grade wafers, a more elaborate procedure is recommended.

4.4 Gas Supplies

Gases used for film deposition and doping were silane, phosphine and diborane and were supplied by Matheson Gas Products. To allow for variation of several orders of magnitude in dopants/silane gas ratios silane in concentrations of 1%, 3% and 10% in Ar was ordered while the dopant gases phosphine and diborane were obtained in concentration of 0.01% and 1% in Ar. This enabled us to have a range of up to five orders of magnitude in the dopant-to-silane gas ratio. Generally the deposition pressure was set at 3 torrs and the total gas flow was set at 80 s.c.c./min.

4.5 Back Electrode

The back electrode was vacuum evaporated aluminium, which was then annealed at 450°C for 10 minutes to form an ohmic contact. Before the aluminium was evaporated the back side of the cell, which was contaminated with a doped layer, was chemically etched

away. It should be pointed that this procedure is not an industrial standard for solar cell fabrication, but it is convenient for the present purpose.

4.6 Top Surface Electrode

Unlike other amorphous silicon solar cells, which have much lower sheet resistance and which must have transparent thin film electrodes, the top electrode on our HJ-cell is a metal. We used aluminium.

For quick testing and comparison a letter "E" electrode was used as shown in Figure 4.6.1. The electrode was formed by evaporation through a mask. About 40% of the cell area was under the electrode shadow and therefore a high efficiency was not expected.

After suitable fabrication conditions had been identified using the "E" electrode, a new electrode design was used. The shade area of the new electrode is reduced to about 8% of the cell area. The new electrode configuration is shown in Figure 4.6.2. It is fabricated by a lithographic technique in our laboratory. The dimensions and design are such that it is easily achievable in industries using the conventional screen printing technique.

4.7 Top Surface Coating

The top surface coating serves several functions: to protect the electrode from oxidation , to eliminate surface states,

THE LETTER "E" ELECTRODE

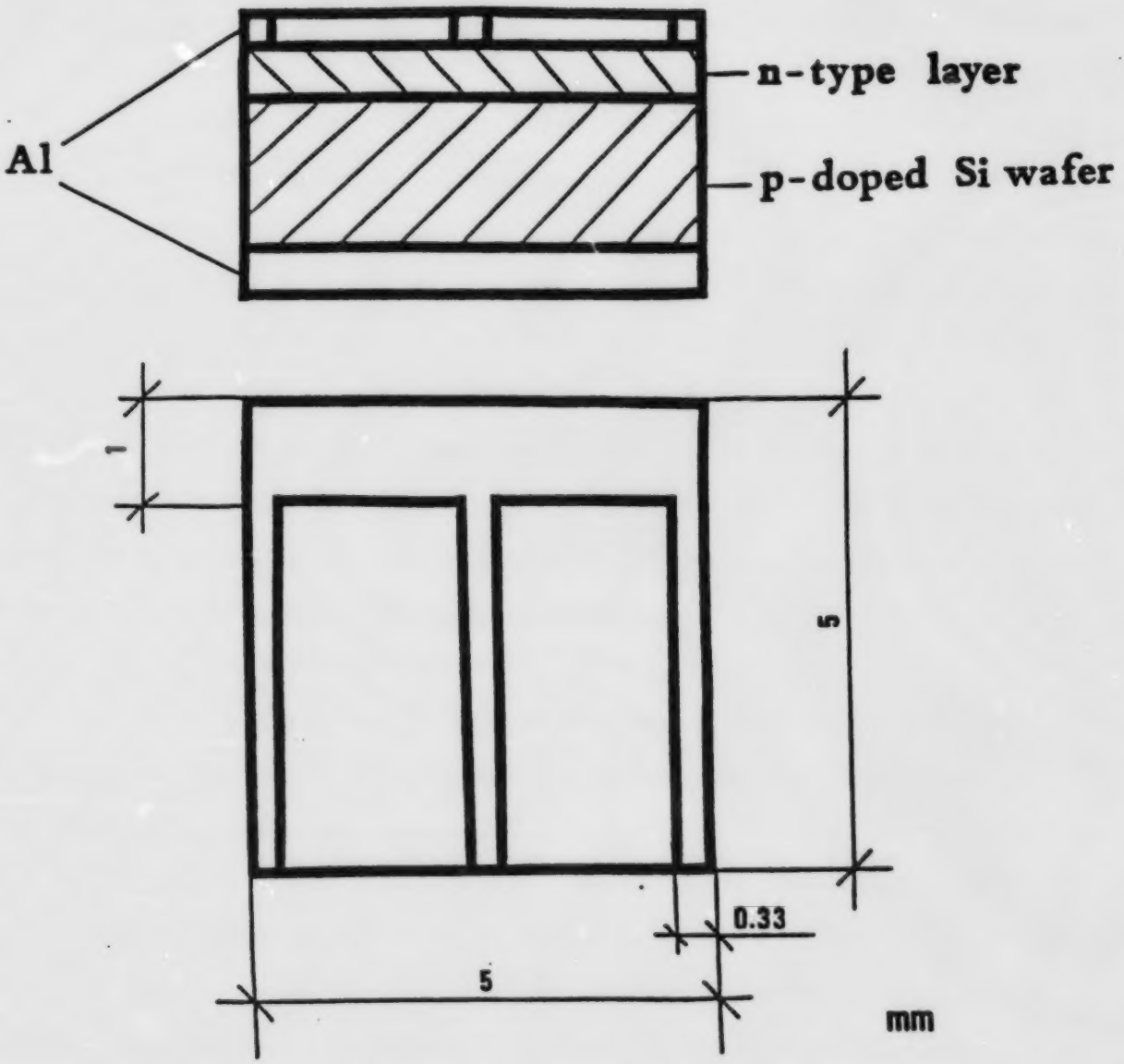


Figure 4.6.1

NEW DESIGN OF THE TOP METAL ELECTRODE

The electrodes are deposited on the samples in our laboratory by lithography, but the design was made so that it can be produced by usual processes used in crystalline silicon solar cell production such as the screen printing method (we do not have a screen printing set up). The dimensions of the electrodes are shown below:

Area-- 1 in x 1 in
Line-- Length: 0.8 in
Width : 0.0025 in
Spacing: 0.0475 in

The cross line leading to external contact points has a tapering width.

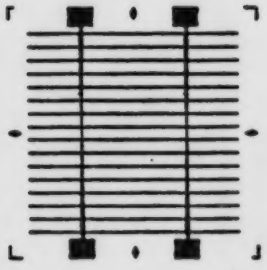


Figure 4.6.2

and to prevent reflection of the incident light.

The electrode material we used is aluminium. Although the HJ solar cell is stable, it was found that the electrodes can deteriorate over long periods of time, especially if the electrode layer is not sufficiently thick. A coating protects the electrode to a certain degree.

The surface of aSi films is believed to be less ideal than a single crystal surface. Elimination of surface states by a dielectric coating enhances cell performance. The aSi surface can reflect as much as 30 % of the incident light. An anti-reflection coating would undoubtedly increase the efficiency significantly.

We found that a layer of liquicoat Si (ZLI-2132) can perform all three purposes fairly satisfactorily. The anti-reflection is not perfect, because we did not try to control the thickness to any precision. The increase in the performance of the cell is already close to 30%. The process is no more difficult than dipping the finished cell in this liquid.

In a later stage an indium-tin-oxide (ITO) coating was also used. ITO was produced by vacuum evaporation. The results of these experiments are very encouraging.

4.8 Measurement of Conversion Efficiency

The cell characteristics listed in section 5.1 and 5.2 should not be taken in absolute terms. Partly it is because we did not have a suitable standard solar simulator and partly because

these were comparative studies. The top electrode for these cells was the letter E and there was no antireflection coating. We found it was sufficient for effective and efficient comparison studies.

Results presented in Section 5.3, 5.4, 5.6, and 5.7 could be considered in absolute terms. Several of our cells, a commercial cell supplied by TPK and another cell labelled as " supercell " supplied by Edmund Scientific were brought to Solar Energy Research Institute (SERI) for efficiency measurement and standardization. The other cells of ours were directly calibrated against the " supercell " measured at SERI.

5. RESULTS AND DISCUSSION

5.1 HJ-cells Fabricated from Different a-Si Films on the Same Substrate Wafer Material.

The HJ-Cells are formed of two materials: aSi and cSi. Matching the two is essential for good performance of the solar cell. The first part of our work is to have an overall scan of the parameters characterizing aSi and cSi. In the following we shall only present results of n-type (phosphorus doped) aSi on p-type (boron doped) c-Si wafers. Results of the p-type film on n-type substrate are similar, differing only in details.

As we mentioned above, the figures in the tables should not be taken as absolute values. The cells are to be compared

relatively among each group listed in the tables.

The LPCVD films at different dopant gas mixture ratios (phosphine to silane) were deposited on substrate wafers. In the case of the Test Grade wafers obtained from Monsanto (resistivity: 5-15 ohm-cm), the results (Table 5.1.1) indicate that a more heavily doped aSi (4×10^{-3}) top film gives a higher efficiency. On the other hand, on the Prime Grade wafer of resistivity 0.75-1.25 ohm-cm a less heavily doped top layer (4×10^{-4}) is preferred (Table 5.1.2). On Test Grade wafers of 0.005-0.02 ohm-cm resistivity, the same is true (Table 5.1.3). Similar results are also observed in solar grade substrates (Tables 5.1.4 and 5.1.5).

5.2 HJ-cells Fabricated from the Same a-Si Film on Different Substrate Wafers

Characteristics of HJ-cells fabricated from wafers of different grades (TG = Test Grade, PG =Prime Grade, and SG =Solar Grade) of different resistivity with the same top layer are given in Table 5.2.1 (dopant gas ratio 4×10^{-4}) and in Table 5.2.2 (dopant gas ratio 1×10^{-3}).

Several general conclusions can be drawn from results listed in these tables (5.1.1, 5.1.2, 5.1.3, 5.1.4, 5.1.5, 5.2.1, and 5.2.2):

(a) A high resistivity wafer requires a highly doped top layer. On the other hand, when the resistivity of the wafer is low,

TABLE 5.1.1

np-HJ-CELLS: differnet films on
p-type test grade wafers (5-15 Ω-cm)

Dopant Ratio	4×10^{-4}	1×10^{-3}	4×10^{-3}
Cell Number	E168-2	E152-2	E154-2
I_{sc}	6.3 mA	8.6 mA	11.3 mA
V_{oc}	0.43 V	0.35 V	0.47 V
FF	33 %	37 %	37 %
Product	0.89 mW	1.11 mW	1.97 mW

TABLE 5.1.2

np-HJ CELLS: different films on
p-type Prime Grade (0.75-1.25 Ω-cm)

Dopant Ratio	4×10^{-4}	1×10^{-3}
Cell Number	E167-1	E146-2
I_{sc}	6.6 mA	6.4 mA
V_{oc}	0.37 V	0.58 V
FF	50 %	32 %
Product	1.22 mW	1.19 mW

TABLE 5.1.3

np-HJ CELLS: different films on
p-type test grade wafers (0.005-0.02 Ω-cm)

Dopant Ratio	4×10^{-4}	1×10^{-3}
Cell Number	E156-1	E159-2
I_{sc}	3 mA	0.2 mA
V_{oc}	0.13 V	0.05 V
FF	27 %	40 %
Product	0.11 mW	0.004 mW

TABLE 5.1.4

np-HJ CELLS: Different films on
p-type solar grade (0.1-0.5 Ω-cm)

Dopant Ratio	4×10^{-4}	1×10^{-3}
Cell Number	E142-2	E140-1
I_{sc}	7.3 mA	5.3 mA
V_{oc}	0.35 V	0.35 V
FF	37 %	36 %
Product	0.95 mW	0.67 mW

TABLE 5.1.5

np-HJ CELLS: different films on
p-type solar grade wafer (0.005-0.02 Ω-cm)

Dopant Ratio	1×10^{-4}	4×10^{-4}	1×10^{-3}
Cell Number	E143-2	E142-1	E148-1
I_{sc}	0.1 mA	1.8 mA	1.7 mA
V_{oc}	0.06 V	0.15 V	0.05 V
FF	52 %	24 %	25 %
Product	0.03 mW	0.06 mW	0.02 mW

a lightly doped top film gives a higher efficiency. For example, an $1x10^{-3}$ aSi film on a 5-15 ohm-cm wafer is better than a $4x10^{-4}$ film aSi on the same wafer, but the $1x10^{-3}$ aSi film on a 0.75-1.25 ohm-cm wafer is not as good as the $4x10^{-4}$ aSi film on the 0.75-1.25 ohm-cm wafer.

(b) Efficiency of HJ-cells fabricated on Solar Grade wafers is only slightly smaller than those fabricated on the Test Grade or Prime Grade when their resistivity lies within the same range. (In this comparison, we exclude wafers having resistivity 0.005-0.02 ohm cm.)

(c) Wafers of resistivity 0.005-0.02 ohm-cm produce poor HJ-cells even for top films with 4×10^{-4} dopant gas ratio. This would suggest that we should lower the dopant concentration even more, or alternatively use a top film with a graded concentration. The latter is preferred, because we would like to retain the attractive feature of the use of metal electrodes in the HJ-cells.

5.3 Results of Finished Cells

A few cells were selected and sent to Solar Energy Research Institute, USA for I-V measurements. The fabrication conditions of the top film of these cells were: deposition temperature 620°C, phosphine/silane gas ratio 4×10^{-3}, and time of deposition 60 minutes. The bottom silicon wafer was test grade wafer of resistivity 5-15Ωcm . The top electrode was of the new design with about 8% of shade area. The original size of the cells

TABLE 5.2.1

np-HJ-CELLS: the same film (Dopant ratio = 4 X 10^{-4}) on different substrate wafers

WAFER (Ω-cm)	30-60 SG	5-15 TG	1-2 SG	0.75-1.25 PG	0.1-.5 SG	0.005-0.02TG	0.005-0.02SG
Cell #	E168-1	E168-2	-	E167-1	E142-2	E156-1	E142-1
I_{sc}	6 mA	6.3mA	-	6.6mA	7.3mA	3 mA	1.8mA
V_{oc}	0.37 V	0.43 V	-	0.37 V	0.35 V	0.13 V	0.15 V
FF	36 %	33 %	-	50 %	37 %	27 %	24 %
Product	0.8 mW	0.89mW	-	1.22mW	0.95mW	0.11mW	0.06mW

TABLE 5.2.2

np-HJ-CELLS: the same film (Dopant ratio = 1 X 10^{-3}) on different substrate wafers

WAFER (Ω-cm)	30-60 SG	5-15 TG	1-2 SG	0.75-1.25 PG	0.1-.5 SG	0.005-0.02TG	0.005-0.02SG
Cell #	-	E152-2	E148-2	E147-2	E140-1	E159-2	E148-1
I_{sc}	-	8.6mA	7.6mA	6.8mA	5.3mA	0.2mA	1.7mA
V_{oc}	-	0.35 V	0.37 V	0.44 V	0.35 V	0.05 V	0.05 V
FF	-	37 %	38 %	36 %	36 %	40 %	21 %
Product	-	1.11mW	1.07mV	1.08mW	0.67mW	0.004mW	0.02mW

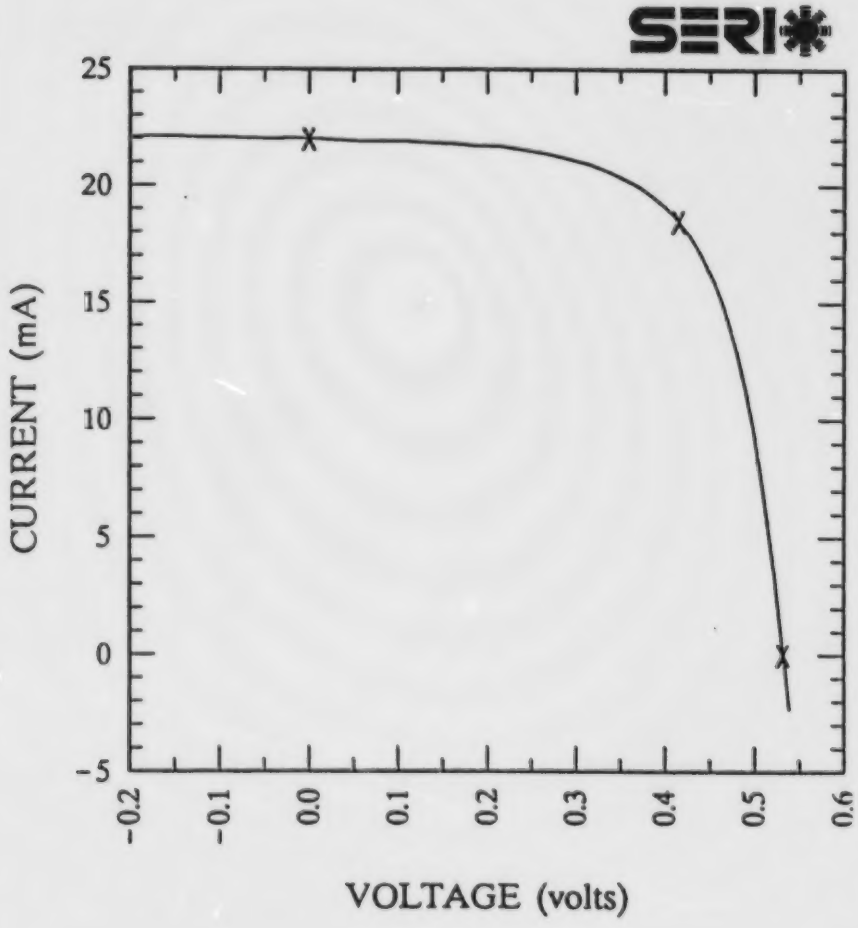
covered an area of 2.54 cm x 2.54 cm (See Figure 4.6.2). But the cells sent for measurement were about 1 cm x 1 cm, which fits to the size of our light source. These cells had a silicon oxide protective coating which also served as an anti-reflection coating. This coating resulted in an increase in efficiency by more than 25%, particularly in current output.

Figure 5.3.1 and Figure 5.3.2 show the areas and I-V characteristics of two cells E203-5 and E203-6 respectively. The areas of the cells were 1.061 cm^2 and 1.083 cm^2 ; V_{OC} = 0.53 volts and 0.54 volts; Isc = 22.0 mA and 22.6 mA, fill factor f = 65.6% and 66.4%, and conversion efficiency 7.2% and 7.4% respectively. These results should be compared with the results for the two commercial cells, which were also measured by SERI. The two commercial cells were a solar cell from TPK Solar Systems Inc. and a solar cell labelled as 'supercell' from Edmund Scientific. Their I-V characteristics are shown in Figure 5.3.3 and Figure 5.3.4 respectively. The conversion efficiency of the TPK cell was 5.5% while that of the supercell was 13.3%. The supercell was probably an advanced space quality cell. It had good I-V characteristics: V_{oc} = 0.57 volts, J_{sc} = 34.1mA/cm^2 and fill factor f = 70.5%. The TPK cell had lower values V_{oc} = 0.47 volts, J_{sc} = 24.2mA/cm^2 and fill factor f = 48.9%. The I-V characteristics of our E203-5 and E203-6 cells lie between those of these two commercial cells. We had expected the efficiencies of the supercell and the TPK cell to be about 16% and 10% respectively. TPK Solar Systms Inc. has

UNWO a-Si/Si 1000 W/m² global

Sample: E203-5 Temperature = 25.0°C

Dec. 11, 1989 12:00 pm Area = 1.061 cm²



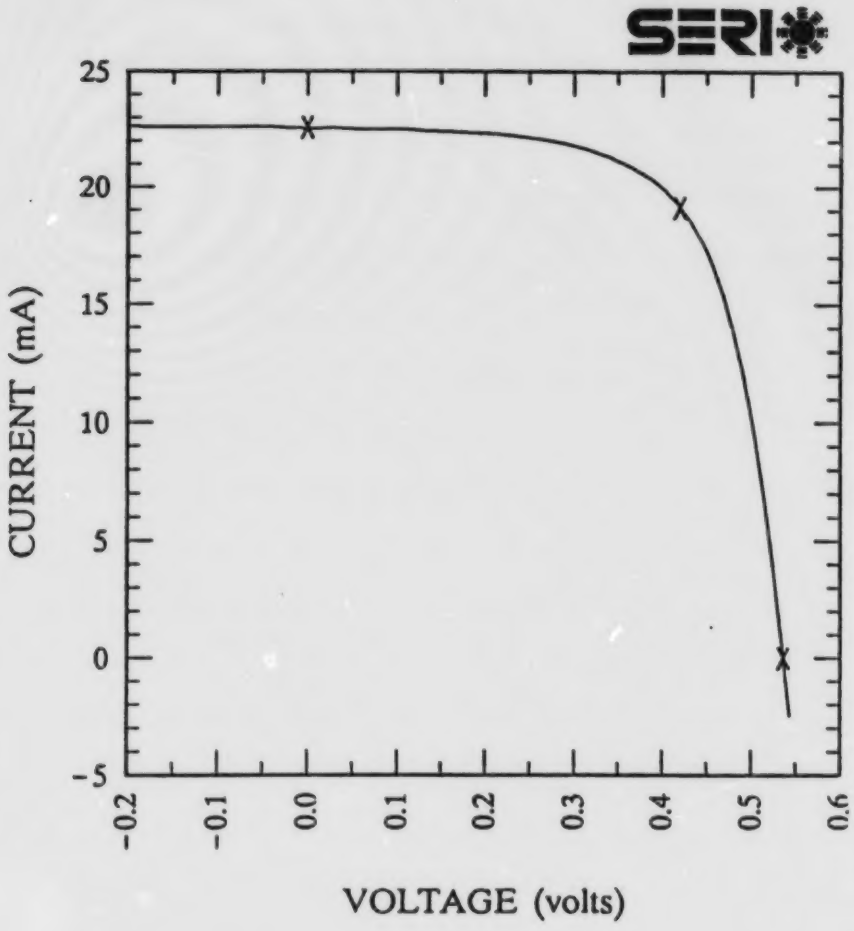
V_{oc} = 0.5322 volts	I_{sc} = 21.98 mA
J_{sc} = 20.72 mA/cm²	P_{max} = 7.67 mW
Fill factor = 65.57 %	I_{max} = 18.48 mA
Efficiency = 7.2 %	V_{max} = 0.4151 V

Figure 5.3.1

UNWO a-Si/Si

Sample: E203-6 Temperature = 25.0°C

Dec. 11, 1989 12:04 pm Area = 1.083 cm²



V_{oc} = 0.5366 volts I_{sc} = 22.58 mA

J_{sc} = 20.85 mA/cm² P_{max} = 8.04 mW

Fill factor = 66.36 % I_{max} = 19.13 mA

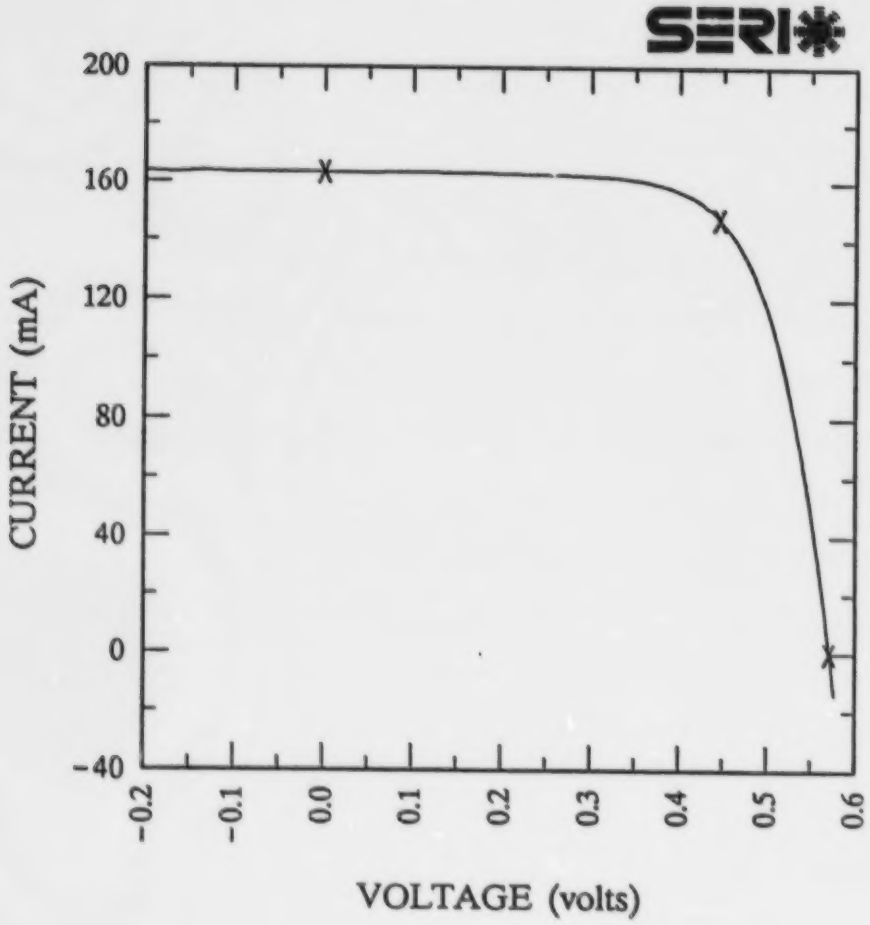
Efficiency = 7.4 % V_{max} = 0.4202 V

Figure 5.3.2

Univ.W. Ontario,mono – Si,global,1000W/m²

Sample: Supercell
Nov. 17, 1989 3:09 pm

Temperature = 25.0°C
Area = 4.940 cm²



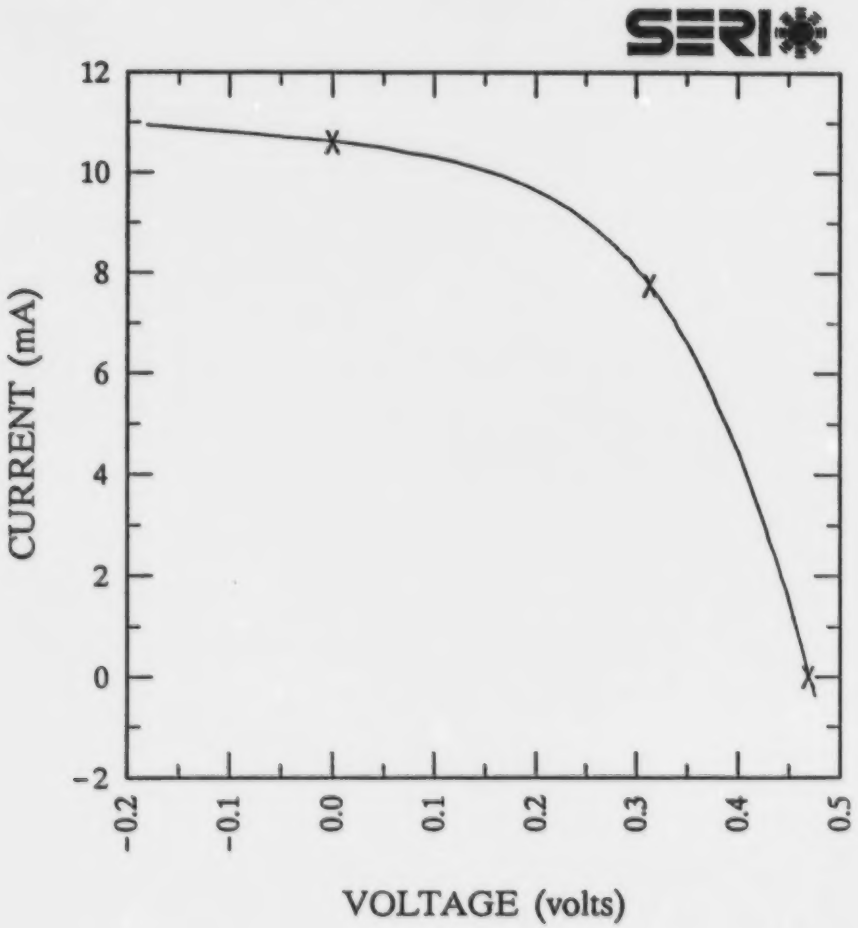
V_{oc} = 0.5712 volts	I_{sc} = 163.4 mA
J_{sc} = 33.08 mA/cm²	P_{max} = 65.8 mW
Fill factor = 70.47 %	I_{max} = 147.4 mA
Efficiency = 13.3 %	V_{max} = 0.4462 V

Figure 5.3.3

Univ.W. Ontario,mono – Si,global,1000W/m²

Sample: TPK
Nov. 17, 1989 3:50 pm

Temperature = 25.0°C
Area = 0.439 cm²



V_{oc} = 0.4692 volts	I_{sc} = 10.60 mA
J_{sc} = 24.15 mA/cm²	P_{max} = 2.43 mW
Fill factor = 48.90 %	I_{max} = 7.76 mA
Efficiency = 5.5 %	V_{max} = 0.3135 V

Figure 5.3.4

reported a semi-automatic technology capable of volume production of solar cells with average efficiency greater than 12% (5.3). It appears that the cell we got from them is not representative of the product.

An efficiency of 7.4% for a solar cell does not seem very impressive on the surface when compared with a world record of over 20%. But after one considers the following aspects one would have a better appreciation of our achievement: i) our HJ-cells surpass HJ-cells produced by the glow-discharge method which have efficiency less than 1% ; ii) most of the photovoltaic action in our cells occurs in the deposited thin film, which absorbs almost all the visible light and a large fraction of infra-red radiation; so that iii) the quality requirement for the silicon wafer substrate could significantly relax; and therefore iv) the cost of the solar cell could be substantially lowered; on the other hand v) a conventional cell or a high efficiency cell must require a good or super high quality wafer respectively because the diffused layer is part of the original silicon wafer.

5.4. One Cent Wafer Cells

We had tried to secure some lower quality silicon such as metallurgical grade silicon but could not. They were simply not available commercially. Even polycrystalline silicon wafers could not be secured, because they were in short supply and the manufacturers of those wafers had presold all the production capacities. Nevertheless we were able to buy a batch (1000 pieces)

of silicon wafers of no specification costing only 1 cent each. These wafers had rough, unpolished surfaces. They came stacked together without protection. Some very encouraging results were obtained in the fabrication of H-J cells with these low cost wafers under identical conditions as for E203. Typical conversion efficiency of over 5% was obtained for these cells with Voc =0.54 volts, Jsc = 17.3 mA/cm^2, and fill factor = 54.3% .

5.5 Stability Test

Following Thomas, et. al. (5.5.1) sample HJ-cells underwent humidity bake tests at 85^0C at about 90-100% relative humidity. Figure 5.5 shows time variation of cell efficiency under this condition. The degradation in efficiency is slight: over a 12 day period the degradation was less than 5% under these severe, accelerated aging test conditions. This is considered quite satisfactory and acceptable (5.5.2).

5.6 Post-Deposition Treatment

Post-deposition treatment of amorphous silicon thin films is commonplace nowadays. The most popular treatments are hydrogenation, thermal annealing and flash (laser) annealing. Under properly controlled conditions these treatments can improve the quality of the thin film substantially (5.6.1, 5.6.2, 5.6.3). The improvement in quality is reflected as increases in electronic conductivity, photoconductivity, and carrier mobility. Post-

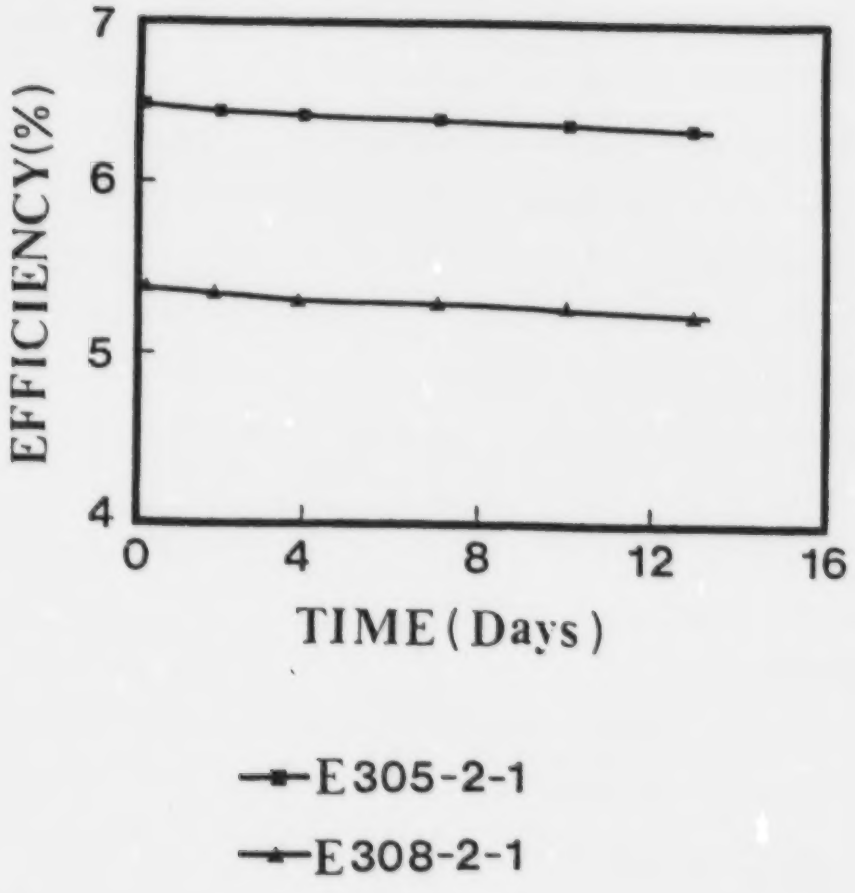


Figure 5.5 STABILITY TEST OF HJ-CELLS

deposition treatment was not part of the contract. However it is a natural extension of the work. We performed some thermal annealing studies which gave very encouraging results. The most interesting of these is a considerable improvement of the conversion efficiency particularly for the lower resistance wafers, that will be described in the following.

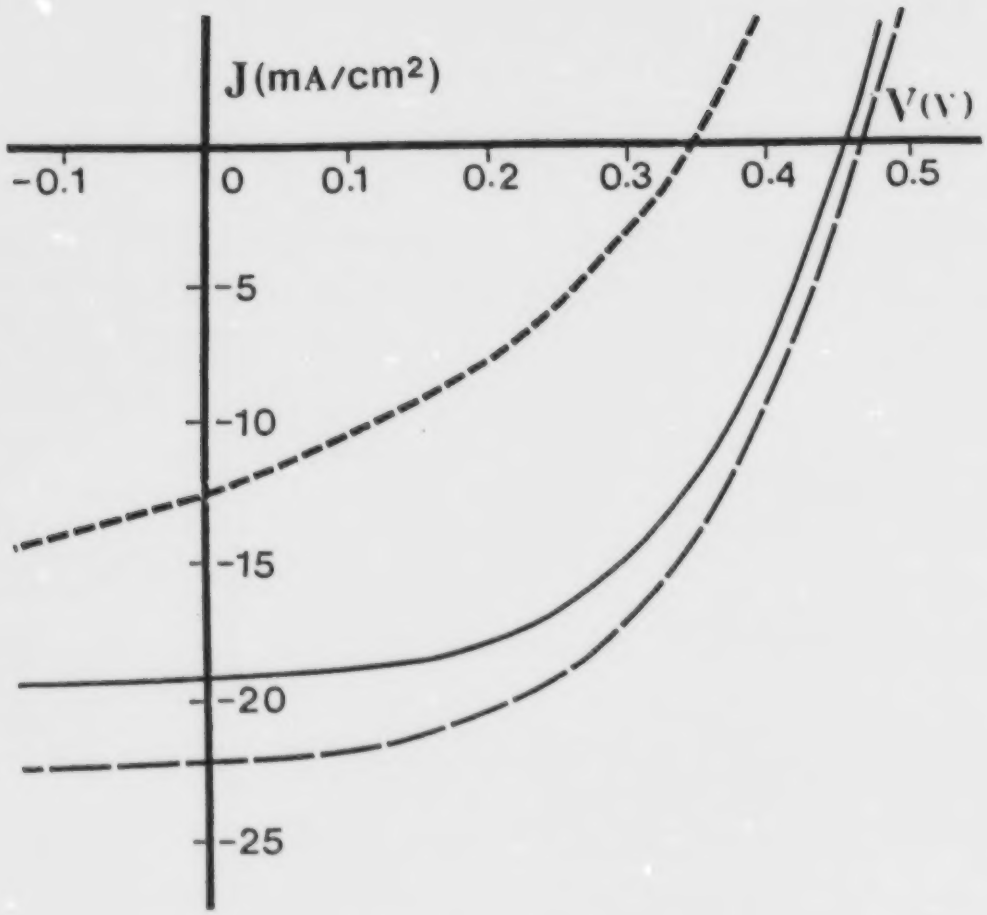
Table 5.6 show results of HJ-cells fabricated on solar grade boron-doped silicon wafers with resistivity 0.1-0.5 ohm-cm and 1-2 ohm-cm. There are three columns of results for each resistivity range wafers namely as deposited (D), annealed (A), and annealed with top protective silicon oxide coating (AC). The deposition conditions were identical in all cases: deposition temperature 620^0C, dopant gas ratio (PH_3/SiH_4) $4x10^{-3}$ and deposition time 60 minutes. The "E" electrode was used for these cells. With the use of proper top electrodes, the efficiency should increase by another 20-30%.

Referring to Table 5.6 we see that for the deposited conditions the I-V characteristics in the case of 0.1-0.5 ohm-cm and 1-2 ohm-cm solar grade silicon wafers are Voc = 0.35 and 0.42 volts, Jsc = 11.8 and 15.2 mA/cm^2, FF = 36 and 50%, and efficiency = 1.5 and 3.2% respectively. Post-treatment by annealing shows improvement in all the I-V characteristics, the Jsc, the Voc, and the fill factor and eventually the conversion efficiency. Their respective I-V characteristics are Voc = 0.48 and 0.51 volts, Jsc = 18.2 and 18.0 mA/cm^2 , FF = 49 and 56%, and efficiency = 4.3 and

Table 5.6 np-Hj Cells: Post-Deposition Treatment

Wafer,ohm-cm	0.1-0.5, solar gr.			1-2, solar gr.		
Cell #	E312-1-3	E312-1-4	E312-1-4	E312-2-1	E312-2-4	E312-2-4
History *	D	A	AC	D	A	AC
Jsc, mA/cm²	11.8	18.2	21.3	15.2	18.0	21.7
Voc, volts	0.35	0.48	0.49	0.42	0.51	0.53
FF, %	36	49	48	50	56	55
Efficiency,%	1.5	4.3	5.0	3.2	5.1	6.3

History * : D = as Deposited, A = Annealed, AC = Annealed with Coating



--- As Deposit

—— 900°C Annealing

—- Annealing with Coating

Figure 5.6 POST-TREATMENT OF HJ-CELLS

5.1%. That is in the case of 1-2 ohm-cm solar grade silicon the improvement in 60% while in the case of 0.1-0.5 ohm-cm wafers the improvement is by an astonishing 192%. With silicon oxide as top wafers protective and anti-reflection coating the efficiencies of these cells are further improved by another 20%. These are extremely important and very encouraging results. To demonstrate these drastic improvements we display the results for the case of 0.1-0.5 ohm-cm wafers in Figure 5.6 so that the reader could immediately identify the effect.

The best result we have obtained so far for a post-deposition treatment is 8.4% in conversion efficiency with the "E" electrode. The I-V characteristics of this cell (E309-1-3) are Voc = 0.54 volts , Jsc = 22.9 mA/cm^2, and FF = 67%. With a proper electrode design, the efficiency of this cell could increase to over 10%. We consider this is very significant because we have made only minor effort in this direction so far. This process promises to have great potential for further research and development for commercial manufacturing.

It is very encouraging , (see Dr. Thomas' report in Appendix 5.8), to note that there is other work, which can be related to the work reported here, carried out at Carleton University. Efficiencies over 11% were achieved by this analogous process. The work was reported in an M.Eng. Thesis by George Papadopoulis under the supervision of Professor N.G. Tarr.

5.7 Indium-Tin-Oxide (ITO) Top Coating

Research and development in light trapping and absorption have always been drawing considerable attention in photovoltaics. We have been experimenting with indium-tin-oxide (ITO) as a top anti-reflection coating. ITO has some very special physical properties. It is transparent to the solar spectrum; it is electrically conductive; and it is an n^+-doped material. ITO can be processed as a thin film and so an anti-reflection layer can be fabricated. With theoretical and experimental modelling it was found that a layer of ITO with thickness of 850 A would give the best light trapping effect. When this layer of ITO is applied to our HJ-cells a large increase of the short-circuit current is expected. Since ITO is conductive it would help to reduce the series resistance and thus to improve the fill factor. Also when ITO is applied onto a n-p junction the open-circuit voltage is expected to increase because ITO is an n^+-doped material. Table 5.7 shows a typical example for comparison. In this example the cells were fabricated in the same batch and an "E" electrode was used with and without an ITO layer. Without ITO the I-V characteristics are the following: Voc = 0.49 volts, Jsc = 13.5 mA/cm^2, FF = 55%, and efficiency = 3.6%. With ITO, Voc =0.54 volts, Jsc = 20.0 mA/cm^2, FF = 69%, and efficiency = 7.4%. This is a very impressive improvement. It should be remembered that with the use of our new electrode design, the efficiency would increase by another 20-30%.

Table 5.7 np-HJ Cells: Indiun-Tin--Oxide (ITO) Coating

	Without ITO Coating	With ITO Coating
Voc, volts	0.49	0.54
Jsc, mA/cm²	13.5	20.0
FF, %	55	69
Efficienct, %	3.6	7.4

5.8 Study of Manufacturing Potentials

For a new technology to survive and to succeed in the commercial world there are many factors such as financing , marketing and timing. However,the most essential factors are 1) that the product of the new technology serves the needs of society, that is, there should be a market, and 2) that it is competitive with the existing technology. The process developed here is intended to help Canadian photovoltaics industry to supply energy to the public. There is an ever increasing demand for energy in our industrial society. The main problem is the price competitiveness. At present photovoltaic energy cannot effectively compete with the conventional sources of energy, because the cost is too high for widespread terrestrial applications. Therefore the present technology has to be improved or new technologies have to be developed to meet the challenge. In terms of photovoltaics the price of the module per peak watt should be reduced from over $4 to below $2. The cost of silicon wafer accounts for 50-60% of the total production cost of solar cells. Any reduction of wafer cost will have a strong impact on the photovoltaics industry.

One of the objectives of the present contract was to develop a process to use low cost and therefore low grade silicon wafers to fabricate solar cells without too much reduction in cell efficiency. According to our estimate, in conformity with Dr. Thomas' assessment (details see Appendix 5.8---Dr.Thomas' report), equipment and process costs of our HJ-cells would not be much

different from those of diffused junction cells, except that lower temperature is sufficient for our process. There would not be any major problems in scaling up. LPCVD systems are commercially available and the other processes are standard in the industry.

We have been experimenting with silicon wafers of resistivity of 0.005-0.02 ohm-cm and with very low cost wafers costing 1 cent per wafer but with no specifications. These were in place of low cost metallurgical grade silicon, which is not yet commercially available in wafer form. (According to Dr. Thomas, one can envision a 100mm x 100mm wafer that costs less than US$0.50, and then the cost objectives for the process would be met.) We have observed a reduction of efficiency with the above mentioned wafers as expected. We have not been able to produce an HJ-cell with an efficiency over 1% with 0.005-0.02 ohm-cm wafers. With this type of wafers the conventional process does not produce solar cells of high efficiency either. But we have produced HJ-cells with efficiencies over 5% with the one cent wafers. We cannot assess the process effectively and sensibly with respect to cost reduction until we can control the cost and the quality of the low grade silicon wafer for the experiment.

The high price of the present photovoltaic products is also intimately linked to the low efficiency of solar cells. A continual search for processes to increase the efficiency is a constant challenge worldwide. Our process with good wafers could produce cells of efficiency over 10%. With further modification and

improvement of the process the efficiency can be improved to compete with the traditional process. The work at Carleton University supports this view. With all these as a base for the development and the fabrication of tandem cells, an efficiency exceeding 15% with a high open circuit voltage might be obtained. Dr. Thomas believes that this probably represents the greatest potential of this technology.

6. CONCLUSIONS

Single junction photovoltaic cells with a novel structure have been designed and developed as part of this contract. This new single junction structure designated as HJ-cell, is formed by depositing a doped silicon thin film (aSi) on the top of an oppositely doped silicon crystalline wafer (cSi). This HJ-cell is developed with the following objectives: i) to achieve conversion efficiencies competitive to the commercial terrestrial solar cells, and ii) to reduce the cost of the wafer by increasing the contribution of the top layer in photovoltaic generation.

Matching the top film with the bottom silicon wafer in the development of efficient solar cells is crucial. Experimental results show that only a fraction of a great variety of thin films are suitable. A high resistivity wafer requires a highly doped top layer and vice versa. The best results obtained were that cells were formed by depositing a top n-doped silicon layer at 620°C with a phosphine/silane gas ratio of 4×10^{-3} onto a test grade boron

doped silicon wafer of 5-15 Ω-cm. The I-V characteristics were V_{oc} = 0.54 volt, J_{sc} = 21 mA/cm^2, and the fill factor = 66% resulting in a conversion efficiency 7.4%. The cells underwent a satisfactory stability test. Post-deposition annealing and anti-reflection coatings with indium-tin-oxide have both improved efficiency significantly but not implemented in the final cells yet. One would expect that with these processes implemented in the final cells efficiency over 10% could be readily obtained. Regrettably low quality wafers such as the metallurgical grade could not be obtained for testing to achieve the desired progress to estimate the cost reduction. Further research and development are required.

Dr. Raye Thomas, an industrial consultant, has estimated that the cost of production of solar cells by our process is comparable to the conventional process. With this as a base for the development and the fabrication of tandem cells an efficiency exceeding 15% with a high open circuit voltage would probably be obtained and would be commercially attractive.

7. RECOMMENDATIONS

Based on our success in the development of the new and efficient heterojunction solar cells:

1) We must continue to develop and improve the process of production and to characterize more fully the photovoltaic

generation of the HJ-cell to further increase the efficiencies;

2) We must continue to identify and secure sources of supply of low cost silicon wafer for experiments in order to reduce the overall cost of solar cells;

3) We must develop and explore the tandem cells based on our thin film experience and the success of the HJ-cell;

4) We must seek more financial support to carry out the above stated R and D;

5) We must establish international contacts with industry to standardize our process since at present there is no commercial production of solar cells in Canada;

and

6) Collaboration with Professor N.G. Tarr at Carleton University should be actively sought. It is because there was analogous and related work carried out and there is a commercial LPCVD system at Carleton to be exploited for studying the manufacturing potential.

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9. APPENDICES

Appendix 2

Appendix 3.1.1

Appendix 3.1.2

Appendix 4.2

Appendix 4.3

Appendix 5.8

Appendix 2 Statement of Task

Statement of Work:

Task 1.1 - Preparation: The work schedule contained in the proposal will be revised. The LPCVD system will be overhauled and spare parts ordered. The measurement laboratory will be organized. All members of the research team will be briefed. Test runs will be performed.

Task 1.2 - Identification of Progress Targets: The expected technical progress on the development of aSi: xSi photovoltaic cells during the course of this contract will be identified and submitted to the Scientific Authority for approval. Two sets of goals will be set: one set to be met within the first year of the contract, and the other set to be met by the end of the second year of the contract. As a minimum, these goals will include the expected size, efficiency and yield of the photovoltaic cells produced on various grades of substrate material.

Emphasis will be placed on developing technical goals which can be objectively measured, but other goals may also be identified.

Task 2.1 - Fabricate p - aSi: n - xSi cells: At least 4 types of wafers and polycrystalline substrates will be used, with each fabricated under 4 or more conditions. A minimum of 20 separate batches of cells will be fabricated.

Task 2.2 - Characterize p - aSi: n - xSi cells: The cells fabricated in task 2.1 will be fully characterized. The results of the various measurements will be analyzed to determine the optimal fabrication conditions. Also, special attention will be paid to identifying relationships between the type and quality of the substrates and the efficiency of finished cells.

At least six of the better performing cells will be loaned to the National Solar Test Facility, in Mississauga, Ontario for independent verification of their electrical output characteristics. At the request of the Scientific Authority, one or more cells will be loaned to the Solar Energy Research Institute, Boulder, Colorado for further evaluation.

Task 3.1 - Fabricate n - aSi: p - xSi Cells: At least 4 types of wafers and polycrystalline substrates will be used, with each fabricated under 4 or more conditions. A minimum of 20 separate batches of wells will be fabricated.

Task 3.2 - Characterize n - aSi: p - xSi Cells: The cells fabricated in task 2.1 will be fully characterized. The results of the various measurements will be analyzed to determine the optimal fabrication conditions. Also, special attention will be paid to identifying relationships between the type and quality of the substrates and the efficiency of finished cells.

Task 4 - Preparation for the Study on the Manufacturing Potential: The groundwork will be laid for the study to be undertaken as Task 6. This will include the identification of the persons at the School of Business Administration who will be involved in the study, and the clarification of the role of the various people involved. This task will culminate in a brief report outlining the scope, objectives, and procedures to be following during the study. The expected roles of the School of Business Administration and the

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Department of Physics at the University of Western Ontario, and Dr. Raye Thomas of TPK International will be defined, and a schedule for the conduct of the study will be presented. This report will be submitted to the scientific authority for approval, at least one month prior to the planned commencement of Task 6.

Task 5 - Interim Report: At the completion of the first year of work an interim report will be issued. This report will include a summary of all work undertaken as part of the contract, and will highlight technical progress achieved to date. A full analysis of the research in relation to the first year goals set in task 1.2 will be included.

If applicable, recommendations for changes to the scope and direction of the work planned for the second year of the contract will be included.

Task 6 - Study in the Manufacturing Potential of aSi: xSi Photovoltaic Cells: This study will be performed by the School of Business Administration at the University of Western Ontario, under the direction of the Department of Physics and with the assistance of Dr. Raye Thomas of TPK International. The primary objective of this study will be to determine the potential for commercialization of the technology developed under this contract.

Some of the items which will be considered in this study are:

- optimal size range of an industrial manufacturing plant
- availability of commercial equipment required for manufacturing the photovoltaic cells
- capital cost of a manufacturing plant, expected lifetime and maintenance requirements of the plant
- material costs and availability
- labour requirements and costs
- expected manufacturing and profitable selling costs of PV cells ($/Wp)
- expected/required yield of cells
- sensitivity of cell to the degree of plant automation
- identifiable non-financial barriers to the establishment of a manufacturing capability
- identification of industrial sectors into which this photovoltaic manufacturing technology could most readily be introduced.

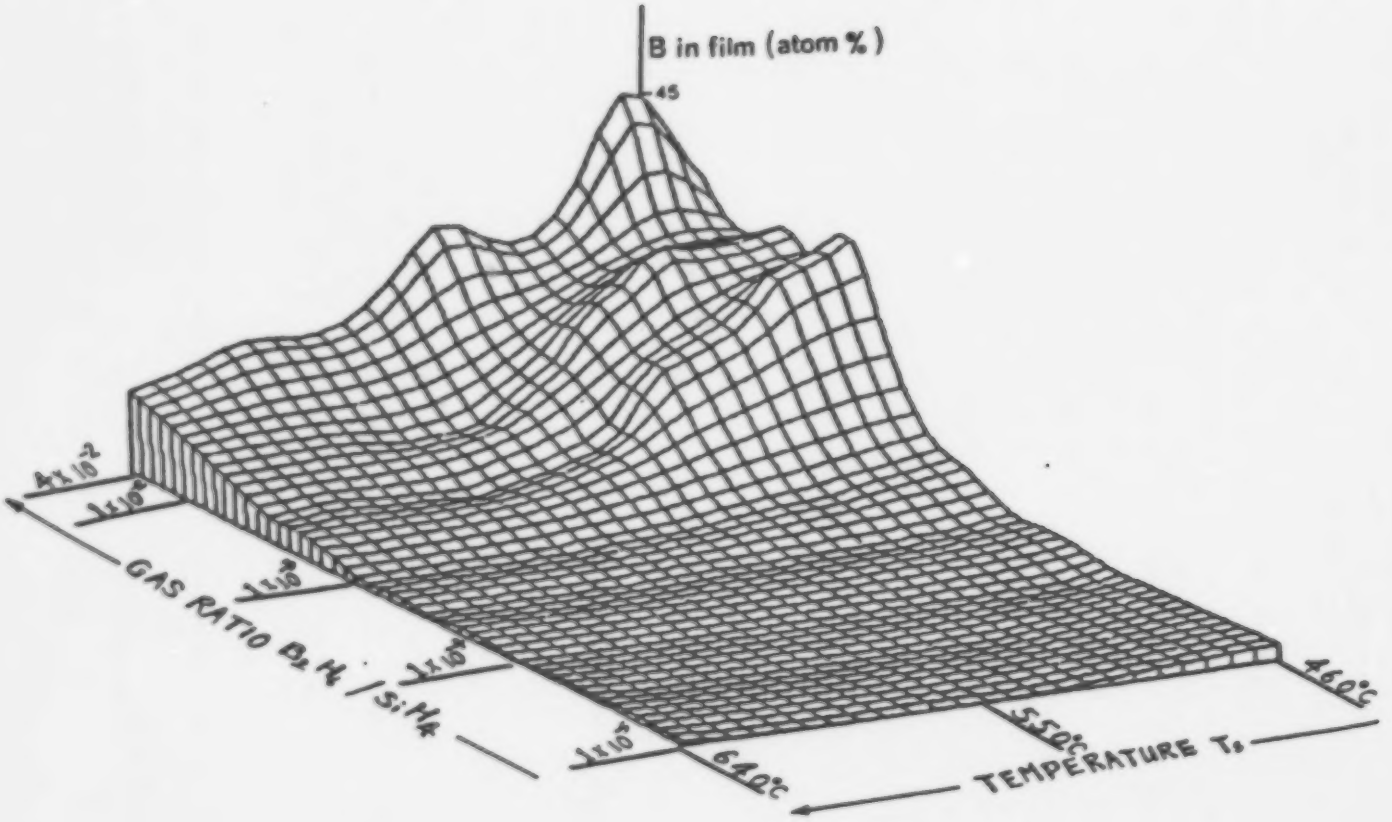
A full report will be written and submitted separately, or as an appendix in the final contract report.

Task 7.1 - Improve Fabrication Procedures: The fabrication equipment and procedures will be improved based on the experience gained during tasks 2 and 3.

Task 7.2 - Final Cell Fabrication: Several runs will be conducted to produce final versions of the optimized cells of both types (p - aSi: n - x Si and n - aSi: p - x Si). Note that the decision on which cells are "optimized" will be made on the basis of the cell structure most likely to lead to commercially viable technology, not merely on the basis of high efficiency (and likely high costs).

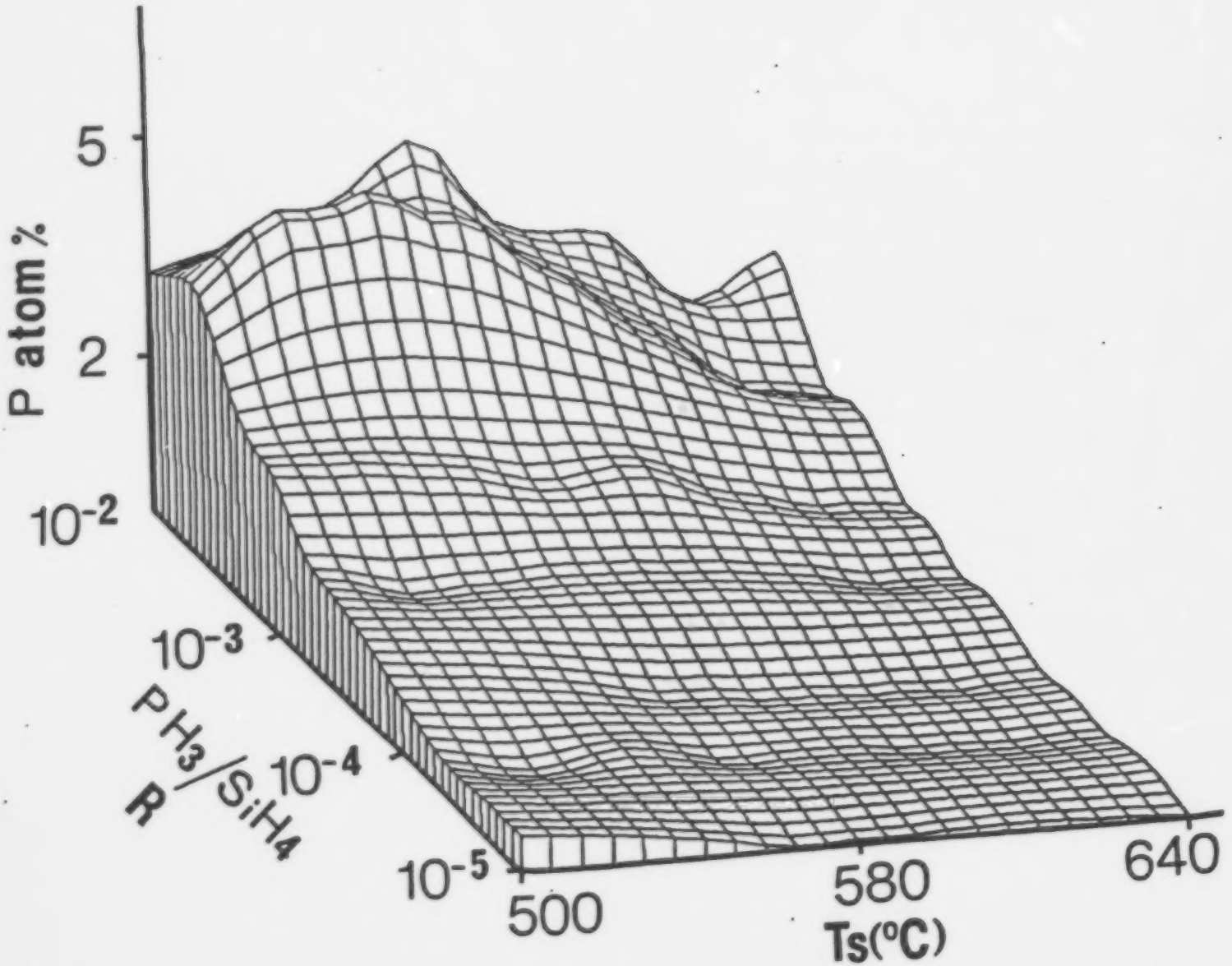
Task 7.3 - Final Cell Characterization: The cells produced in task 7.2 will be subjected to a full characterization and analysis. As before, at least six cells of each type will be loaned to the National Solar Test Facility for independent evaluation, and, at the request of the Scientific Authority, one or more cells of each type will be loaned to the Solar Energy Research Institute for evaluation.

Task 8 - Final Report: A final report covering all work conducted under the contract, with an emphasis on the work conducted during the second year, will be submitted. In addition to covering the technical achievements of the contract work, the report will analyse the most significant remaining technical challenges, if any, and will suggest avenues of research which may lead to ways of overcoming these.



Appendix 3.1.1

Boron Concentration in the Film as a Function of R and Ts



Appendix 3.1.2

Phosphorus Concentration in the Film as a Function of R and Ts

Appendix 4.2

LIST OF SUBSTRATE MATERIALS IN OUR LABORATORY

LOT #	QUANTITY	TYPE	CRYST ORIENTATION	RESISTIVITY (ohm-cm)	GRADE	UNIT PRICE IN U.S.$
80-1	25	N	100	0.005-0.02	TEST	3.25
2	25	N	100	0.9-1.8	PRI	5
48	25	N	100	1-12	TEST	
1	25	N	100	.007-.02	PRI	6
3	11	N	100	4.5-5	PRI	6
4	25	N	100	50-100	PRI	5
5	25	N	111	0.005-0.2	PRI	6.3
6	25	N	111	.4-.6	PRI	5
7	25	N	111	2-4.2	PRI	5
8	5	N	111	100-200	PRI	9
12	25	P	111	.75-1.25	PRI	5
13	25	P	111	3.5-8	PRI	5
14	25	P	111	10-20	PRI	5

80-2	25	P	100	0.005-0.02	PRI	6.5
80-3	50	P	100	0.005-0.02	TEST	3.5
11	15	P	100	5-25	PRI	
47	25	P	100	5-15	TEST	
47	8	P	100	5-15	TEST	
9	2	P	100	0,01-0.02	PRI	5
10	19	P	100	5-15	PRI	5
15	50	P	100	.005-.02	SOL	1.5
16	50	P	100	0.1-0.5	SOL	
17	50	P	100	1.-2.	SOL	1.5
18	50	P	100	10-30	SOL	1.5
19	50	P	100	30-60	SOL	1.5
20	50	P	111	.005-.02	SOL	1.5
21	50	P	111	0.1-1.0	SOL	1.5
22	50	P	111	1-3	SOL	1.5
23	50	P	111	10-20	SOL	1.5
24	50	P	111	60-100	SOL	1.5
25	50	N	100	.005-.02	SOL	1.5
26	50	N	100	0.1-1	SOL	1.5
27	50	N	100	2-4	SOL	1.5
28	50	N	100	9-20	SOL	1.5
29	50	N	100	40-60	SOL	1.5

30	50	N	111	.005-.025	SOL	1.5
31	50	N	111	0.1-1	SOL	1.5
32	50	N	111	1-2	SOL	1.5
33	50	N	111	9-20	SOL	1.5
34	50	N	111	40-60	SOL	1.5
101	1000		No Specifications			0.01

(PRI = Prime grade, TEST = Test grade,
and SOL = Solar grade)

Appendix 4.3

WAFER CLEANING PROCEDURE

(MODIFIED FROM THE RCA LABORATORY SCHEME)

1. Fill two beakers to 27.5 oz (80 cc) with deionized water (DIW).
2. Add 30 % electronic grade hydrogen peroxide to 35 oz (105 cc) in both beakers.
3. Turn the hotplate to Low.
4. Wait for the solution to reach approximately 60 C.
5. Add ammonium hydroxide (30 %) to 40 oz (120 cc) in the first beaker.
6. Place the wafer in NH_4OH mixture for 10 minutes.
7. Flush the wafer with DIW.
8. Add HCl to the second beaker, reaching a volume of 40 oz (120 cc).
9. Place wafers in the HCl mixture for 10 minutes.
10. Flush wafers with DIW.
11. Fill a plastic beaker with DIW to 100cc.
12. Add 50% HF to the 105 cc mark.
13. Dip the wafer in HF solution for 30 seconds.
14. Flush the wafer with DIW.
15. Place the wafer in a beaker with DIW in an ultrasonic cleaner for 5 minutes.
16. Dry the wafer in an isopropanol vaporizer.

Appendix 5.8 Study of Manufacturing Potential

Dr. Raye Thomas' Report

ASTROPOWER CANADA LTD.

REPORT
TO
UNIVERSITY OF WESTERN ONTARIO

ON

TECHNOLOGY AND ECONOMICS

OF

HETEROJUNCTION AMORPHOUS SILICON SOLAR CELL PRODUCTION

BY

RAYE E. THOMAS

November, 1989

1. INTRODUCTION

There are two key tests of any solar cell process to determine if it has a future in the Photovoltaics industry. The first test is whether the technology can yield high efficiency stable solar cells. The second test is an economic one. Can the technology yield solar cells which meet industry cost objectives in terms of Dollars per peak watt.

The program of development in the Amorphous Silicon Research Group at the University of western Ontario is aimed at realizing a heterojunction solar cell structure consisting of amorphous silicon on a low cost silicon substrate. The resultant cell should be amenable to volume production in the same way the homojunction crystalline silicon cell is, have good stability and be low cost since it should be substrate insensitive. The Author's role in this project was to assess the technology on a periodic basis, and to consider the economics of the process.

This report addresses the technology itself, examines the results achieved, looks at the prospects for future development, and at the possibility of scaling it to a large volume throughput. It compares the process with other silicon based technologies. Recommendations are made for future work at UWO.

2. THE STRUCTURE

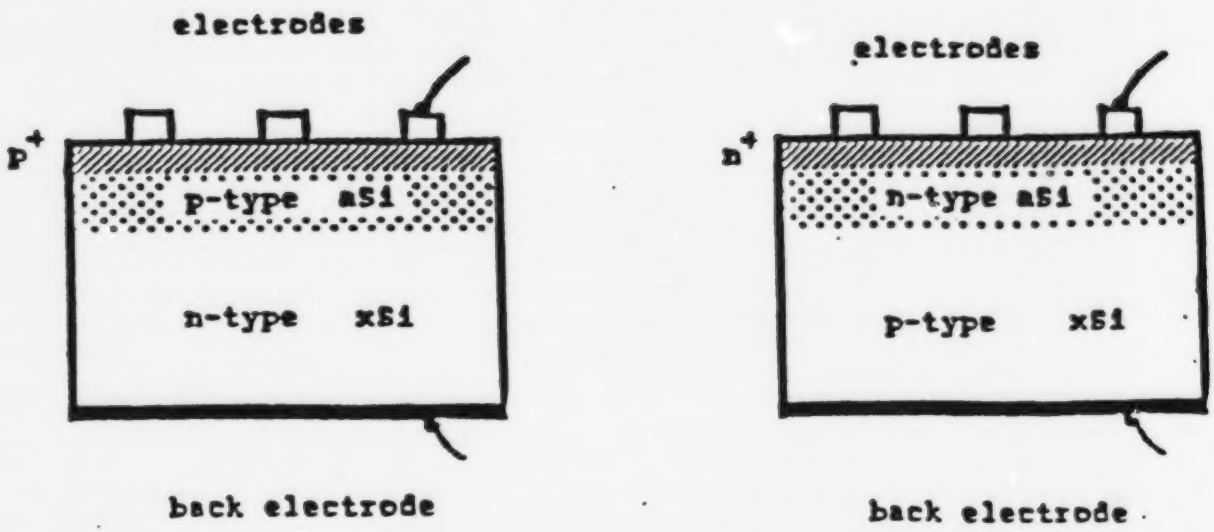
The two possible heterojunction structures of interest for this study are illustrated in Figure 1. There are two basic ingredients, viz. a silicon substrate, and an oppositely doped amorphous silicon layer. Doping of the substrate may be either n type or p-type. A two layer a-silicon structure is required, either a p^+p or an n^+n layer.

The Substrate. In developing this structure, the main role conceived for the substrate is primarily to lend physical strength, and not have it play a major role in defining the photovoltaic output of the cell. This means that virtually all the PV activity should be in the amorphous layer, so that the substrate could in theory be noncrystalline in nature, so long as it contributes little to series resistance in the cell. It also means that the purity of the material should not be an issue. Metallurgical grade silicon could be used with the resultant cost savings which are realized by not having to purify the silicon to semiconductor grade. Since metallurgical grade silicon is normally naturally doped p-type, the second structure of Figure 1 would be the relevant one. Most of the experimental results provided were for the n-p structure.

There is, in fact, a second prospect for this structure, one which was not a subject of this investigation. This relates to the ability to make a high efficiency solar cell by low temperature processes only. The substrate does not have to be subjected to high temperature during the deposition of the amorphous silicon. Thus if a high quality substrate is employed, the well known effect of decreasing minority carrier lifetime as the temperature exceeds 450 to 500°C is avoided. Although this was not a subject of the present investigation, it should be considered in the future.

The Amorphous silicon layer. The requirements for the amorphous silicon layer are that it dominate the PV behaviour, and that it be stable. The former means that there must first be deposited a lightly doped, almost intrinsic layer, followed by a heavily doped layer. The material must have a high absorption coefficient for photons. Rapid deposition for of many substrates at a time must be possible. Low pressure chemical vapour deposition (LPCVD) appears ideal, since it is in widespread use in the microelectronics industry for depositing materials on up to 500 silicon wafers at a time. It can also be plasma or otherwise enhanced to speed up the rate. Moreover, the temperature of deposition can be readily varied, changing the nature of the material from amorphous to microcrystalline, while still keeping absorptivity high. The test of stability can be met in the LPCVD matrial, since the group at UWO have already demonstrated this very well in the literature.

FIG 1 HETEROJUNCTION SOLAR CELLS



(n,p) -aSi: amorphous silicon or microcrystalline silicon in a matrix of amorphous silicon. These materials are produced from our own LPCVD system.

(p,n)-xSi: either single crystalline silicon wafers or lower grade crystalline material like crystalline ribbons of Si, or polycrystals.

3. TYPICAL PROCESS SEQUENCE

With the exception of the deposition of the amorphous silicon layers, the process sequence to make this type of solar cell resembles that for a diffused junction solar cell. A typical process sequence would be as follows:

Heterojunction Cell

Prepare substrate
- Chemical etch/clean

Deposit intrinsic layer
-LPCVD low temperature

Deposit n or p layer
-LPCVD low temperature

Deposit conductive oxide
-SnO_2 or ITO

Contact Metallization
-evaporation at present
-screen printing possible?

Characterize

Diffused junction cell

Prepare substrate
-Chemical etch

Diffuse phosphorus
-High temperature

Etch off oxide
-HF etch

Plasma etch for junction separation

Contact metallization
-Screen printing

Deposit AR coating

Characterize

In the above process sequence, deposition of two amorphous silicon layers substitutes for the phosphorus diffusion and oxide etch of the diffused junction cell. There is little saving of time, so the potential advantage of the heterojunction cell is in the benefits to be derived from low temperature processing. The diffused junction cell also needs a plasma etch to separate the front junction from the back junction. If a large area LPCVD system were used for the heterojunction process, there would also be a-si on the back of the cell. This would normally be etched off, but since it should be easy to penetrate the thin layer by the back contact, etching may not be necessary. The conductive oxide layer is essential for low contact resistance on the front surface as well as to give the surface good anti-reflective properties. There is an analagous AR coating process in the diffused junction cell. The contact metallization process is required in both cells. For the diffused junction cell, the screen printed contacting process is well developed and known to be a low cost one. For the heterojunction process, it is not known whether screen printing can work (it can on the back of the cell). Because printed silver contacts require high temperatures to fire, it is doubtful if they can be adapted to the front of the cell. To date for the front of the cell, evaporated aluminum and pattern definition by photolithography has been used. This does not lend itself to volume production. Perhaps laser patterning may be economical in the future as is used in many of the a-silicon processes.

In examining the two processes, there is little inherent advantage of the heterojunction structure. However, if one looks beyond the process to the substrate, then the process may

make sense. The question to answer is: Can the amorphous silicon layers take over most of the photovoltaic action? If they can, then the substrate material can be downgraded, perhaps even to metallurgical grade silicon. This would result in a very low cost substrate. If this is not possible, then one would have to use equivalent substrates to those used in the diffused junction cells. Then with virgin wafers, the minority carrier lifetime in the substrate could be kept higher, since the material would not be subjected to higher temperature processes. Additionally the energy costs for volume production would be lower.

The experiments conducted should be directed at answering the above questions.

4. RESULTS ACHIEVED TO DATE

The major objectives during the period of the contract were to examine the effects of substrate on the characteristics of the resultant solar cells, determine the optimum gas ratios for deposition, establish a contacting procedure, realize 2 Cm x 2 Cm solar cells with 10% efficiencies in normal material and 5-6% in MG silicon, and look at prospects for volume manufacturing.

Effects of Substrate. The research team obtained a number of substrates to experiment with. These included both n- and p-type wafers in premium grade (as used for microelectronics), test grade (reclaimed and often used merely as dummy wafers in diffusion experiments to characterize process) and solar grade (as sawn and tend to be produced from tang and tails of ingots). They were not able to locate Metallurgical Grade material. The samples experimented with ranged from resistivities in the range of 0.002 to 0.02 Ohm-cm to up to 100 Ohm-cm. They also included samples in the 0.05-5 Ohm-cm which is the typical range used in conventional cell manufacture. The results obtained on the samples were inconsistent, but did indicate one thing, viz. that the substrate contributes very significantly to the photovoltaic action. In fact, for higher resistivity materials, the dominant effect would appear to be in the substrate. This suggests that MG silicon would likely result in devices with low efficiencies.

Unfortunately the history of the wafers used was not really known, nor were the group able to properly characterize the wafers prior to their use in processing. This means that even had they been able to make high efficiency cells, it would have been difficult to attribute the high efficiency to any known factors which influence performance.

Surface treatment of wafers. Some experiments were run on surface treatment, and it was found that this did influence the results obtained. A simple DI water clean is sufficient if there is no real surface damage and the wafers are "virgin" ones supplied properly cleaned and packed. If this is not true, then a clean such as the RCA clean is necessary. Some beneficial effects were found by etching and texturizing (thereby reducing surface reflections), even though etching was not done for a long enough period. In particularly if the wafers had an as-sawn surface, etching to remove at least 25 microns of silicon would be necessary.

Dopant gas ratios. In a high-low junction structure such as developed, one would expect to see variations in performance depending on the relative doping levels of the amorphous and crystalline silicon layers. The experiments conducted showed this to be the case. The measured parameters for the solar cells includes short-circuit current, open-circuit voltage, fill factor and maximum power. In examining the results, the only parameter

which seem to be reasonably consistent is the current. This indicates that for lightly doped substrates, best results are obtained for more heavily doped amorphopus layers. This is consistent with most of the current generation being in the substrate. For the more heavily doped substrates (lower resistivities), the substrate is less effective in current generation, so the amorphous layer becomes more critical. Lighter doping in the amorphous layer is thus better for this case.

This latter observation has significance for metallurgical grade silicon, which tends to have lots of impurities and is low resistivity p-type by nature. By properly optimizing a lightly doped amorphous layer, one might be able to achieve a reasonable efficiency with the heterojunction cell in poor material. This has not been demonstrated in the current project, but could be a significant topic for continued study.

Contacting Procedure. In the work reported, contacts were made using deposited aluminum defined in pattern by photolithography. The pattern most used was an E shape which was not a fine grid, hence would result in much of the surface being shadowed, and low fill factors. This would mask many of the results achieved, so was not a good choice. A finer grid was used in some experiments with better results. Aluminum is not a good choice in practice, since it is difficult to interconnect solar cells using this material. Further, the use of photolithography is not desirable for solar cells since it does not lend itself to high volume low-cost production. Few detailed experiments have been carried out with other materials, hence one is not able to determine whether volume production techniques can be developed. Some experiments were conducted using deposited silver. In the results reported even 5 seconds at 600°C was sufficient to penetrate through the amorphous material. No experiments were carried out with screen printed silver paste. Since this material will have different characteristics from deposited silver, one can not draw any valid analogies from the deposited silver results. This clearly is an area for detailed study. In particular, the effects on the amorphous material of raising the temperature during contact anneal/sinter needs to be studied.

Solar Cell efficiencies. Solar cells were made and their current-voltage characteristics measured and compared against a solar cell originally obtained from TPK (not a high-efficiency one). Unfortunately, the light source was not as good match to the solar spectrum (which would tend to give higher calculated efficiencies than would be the actual case), the light was not uniform, and the measurement technique not well calibrated. Consequently one is not able to conclude what the real efficiencies were. My experience with light of the spectrum used is that it will give efficiencies up to 30% higher than those for the accurate solar spectrum. Hence, for a 0.3 cm^2 cell reported

in March, 1989, to have an efficiency of 11%, the error due to the wrong spectrum could mean that the actual efficiency was of the order of 8%. Clearly attention must be paid to the measurement system. Sample cells have been sent to SERI and to the National Solar Cell Testing Facility for testing. While I have not seen detailed results, verbally I was informed that lower efficiencies were measured. This was attributed to a degradation mechanism, but could also be partially related to the use of a more accurate solar simulator. At present I conclude that the potential of the structure for high efficiency has not yet been demonstrated.

Volume production prospects. This is left for a later section.

Tandem junction cells. While this was beyond the scope of the current contract, the group has done some preliminary experiments on tandem junction cells. The structure being studied is shown in Figure 2. Short circuit current showed an as expected decrease in value from the best single heterojunction structure, while open circuit voltage showed an increase in value. This suggests the potential for a device with high open circuit voltage, and reasonable current. The test structure employed three deposited amorphous silicon layers. An alternative to this is a device with a diffused junction, and then an amorphous junction device deposited on top of this. The structure merits further study.

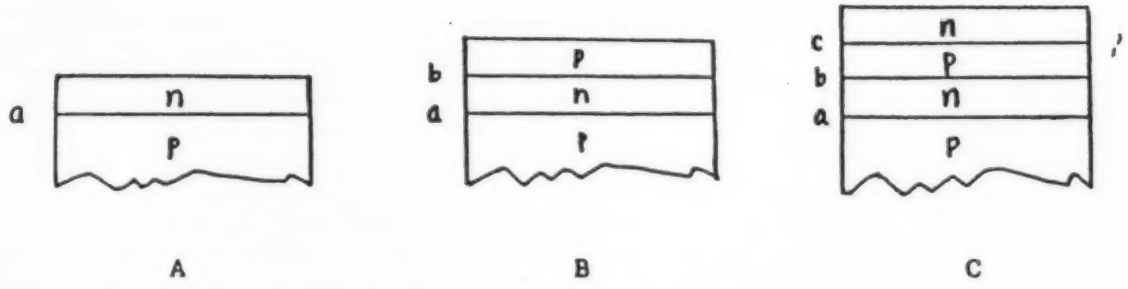


Figure 2. Tandem Cell Structure Investigated.
A. Single junction reference structure
B. Extra layer added
C. Tandem cell

5. ANALYSIS OF RESULTS AND COMPARISON WITH OTHER WORK

The results obtained to date indicate that, while the results fall short of the objectives of the project, the device is worth exploring further. The highest efficiency reported to me was 11% on a small area device. As noted earlier, this needs to be verified with a proper light source and measurement setup where the area is clearly defined. Many of the results presented were masked by the use of a top electrode which was unsuitable for the purpose.

A second problem which has not properly been dealt with is "cross-contamination" due to having to use one chamber for all deposited materials. To avoid this with one chamber, there must be proper cleaning between depositions. The long delays between depositing successive layers, when the cells are exposed to atmosphere (possible contamination and oxide growth) adds a degree of uncertainty to the final results.

A question which was not really addressed by the group is to what degree is the material deposited actually amorphous. Deposition using LPCVD can result in amorphous silicon if the temperature is low enough, but give microcrystalline silicon for higher temperatures and polycrystalline silicon for still higher temperatures. The boundary lines between the three are not clear. However, imposing a degree of crystallinity on the films leads to increased stability. The band gap and absorption coefficients will change as the crystallinity increases. To do a proper tandem structure with the deposited layers having a different band gap from the underlying silicon wafer will require that the material have very small crystal grains or be true amorphous. My impression of the process used is that the material deposited is microcrystalline. This needs to be confirmed with a proper characterization of the layers, and not relying on the results from solar cells.

There is other work which has been carried out which is analagous to the work reported here. This work was done at Carleton University, and has been reported in the literature referring to the device as a "Polysilicon Emitter Solar Cell". The structure studied is shown in Figure 3. As reported in an M.Eng. Thesis by George Papadopoulis entitled "Development and characterization of polysilicon emitter solar cells", (April 1989), the first deposited n-layer is a polycrystalline layer. The second layer is referred to as an amorphous silicon layer. The difference in the two layers is in the temperature and in-situ phosphorus doping level used. The "poly" layer was grown at 627°C with a silane/phosphine ratio of 185/1, while the second layer was grown at 560°C with a ratio of 530/1. Depositions were done in a

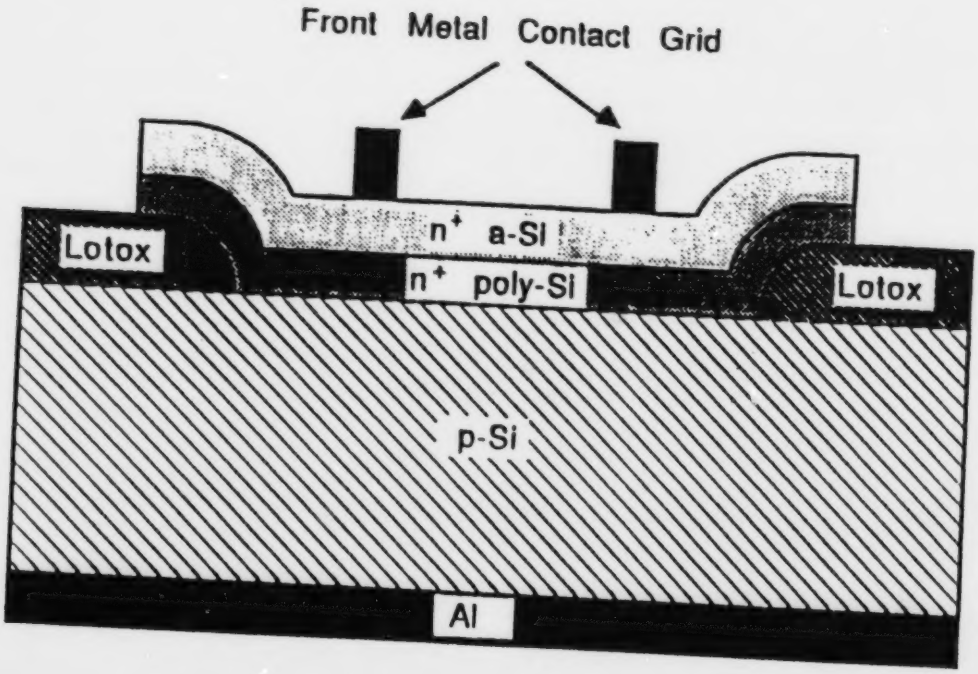


Figure 3 Cross sectional diagram of n^+poly-Si/n^+recrystallized a-Si bilayer emitter solar cell.

commercial LPCVD furnace, and one after the other without removing the samples from the furnace. A final anneal was carried out at 650°C. Short ciruit current densities as high as 32 mA/cm^2, open circuit voltages to 0.67 Volt, fill factors to 0.80 and efficiencies over 11% were achieved with samples with no anti-reflection coatings. Clearly the process has prospects, particularly in achieving high open circuit voltages. It seems to me that both the UWO and Carleton processes should be examined carefully for similarities, and an optimum approach be developed leading to high efficiency solar cells.

6. PROSPECTS FOR SCALING UP AND PROCESS COSTING

Since the process has not yet been demonstrated to be capable of making stable high efficiency cells in low cost substrates, any detailed attempt analyse the future factory size and cost is inappropriate at this time. By referring back to the earlier table comparing the process to the diffused junction cell process, one can get an idea of the relative costs.

Equipment and technology costs for a 1 Megawatt diffused junction line per annual shift of 2000 hours will cost approximately US$1.5 million. Amortizing this over 5 years and including an element for money costs means that there is a cost of roughly $0.35 per Watt peak due to the up front capital cost. Materials used in production (other than wafers) add costs of about $US0.65 per Watt peak. Loaded labour would add a further US$0.25 per Watt. Taken together, the cost for cell production, exclusive of wafers, is of the order of US$1.25. Depending on the material used at present, silicon wafer costs range from US$1.50 to US1.75. This means that cells can be produced currently at a cost of US$2.75 to 3.00 per peak Watt. By using 3 shifts and tripling the output, the cost would be reduced only be about US$0.23 per Watt peak, unless the wafer price would also be reduced at the same time through volume buying. This is not possible at present, since wafers are in short supply.

By highly automating a line and going to 10 MWp per shift, I estimate optimistically that equipment amortization could become as low as US$0.10 per watt, with loaded labour at US$0.15, and materials (other than wafers) could be reduced to at best $0.50 per watt. Thus the cost of making a cell would be at best US$0.75 per Watt peak. This would mean that at today's wafer prices, the cost of a diffused junction cell would be between US$2.25 and US$2.50. Please note that no company is yet in production at this level. Also note that past studies which have predicted that costs could be reduced below US$2.00 per watt peak have always assumed that a 50 MWp line would be necessary.

For the production of the heterojunction cells reported here, there would not be much difference in the equipment costs. To add LPCVD capability to the levels needed, would cost more than diffusion furnaces. However this would be offset by eliminating plasma etching from the process. Assuming that the metallization process can be solved, I estimate that equipment costs would be similar to the equipment costs for screen printed solar cells. Labour and other materials costs should be comparable, so no savings are anticipated with this process.

There are two prospects for cost savings in this process. The first is only possible if one can use lower costs wafers. This does not imply reject wafers from the integrated circuit industry. Rather it represents a fundamental change in the wafer

itself. As noted one prospect is for multicrystalline metallurgical grade wafers. (One of the objectives of the contract were to determine if these could be used). There were some indications for heavily doped wafers that the process could potentially be optimized to make most of the PV action be in the deposited layers. Considerable effort is needed before one can draw valid conclusions on the prospects here. One can envision a 100mm x 100mm wafer that costs less than US$0.50. Then the cost objectives for the process would be met.

The second prospect is for high efficiency cells made using low temperature processing with good wafers. The work at Carleton University has demonstrated that high open circuit voltage is possible, and good current behaviour is also possible. The preliminary tandem cell results at UWO indicate that this structure could be developed also with very high open circuit voltage. Combining the two results, and developing an optimized process, could give devices where the number required in series to charge batteries could be reduced substantially from the number of diffused junction cells used at present. Further if efficiency can exceed 15%, one could see a standard 50 Watt module with only 30 solar cells (as compared to 36 currently used) to charge 12 Volt batteries even in the highest ambient conditions. For a module, the cost would be reduced in practice by a minimum of 20% merely by reducing the number of cells. In my opinion, this probably represents the greatest potential for this technology.

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7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions.

There are several conclusions which can be drawn at this time:

1. The objectives of the project have not yet been met, although solar cells with reasonable efficiencies have been achieved.

2. The ability to use poorer quality substrates has not been demonstrated. There are some indications that one can, by varying deposition parameters, control the relative amounts of contribution of the substrate and the deposited layers to the PV output.

3. There are prospects for increased open circuit voltage in a tandem solar cell based on the approach.

4. The heterojunction structure proces will not result in any real cost savings unless low cost poor quality substrates can be used, or efficiencies and voltages can be increased over those in the best production diffused junction cells.

The results have shown some promise, but considerably more work must be done if that promise is to be capitalized upon.

Recommendations for future work.

There are two types of recommendations I will make. The first type concerns the areas which should be explored further. The second type is specific to the group at the University of Western Ontario.

General recommendations.

1. Using a standard substrate known to be good, or well characterized prior to processing, layers should be deposited with different gas ratios and different temperatures, and fully characterized after processing for doping and crystallinity. This will anable one to selest a desirable set of parameters for deposition.

2. A theoretical study should be undertaken to determine the optimum solar cell structure using amorphous and/or polysilicon deposited layers.

3. A proper etch/cleaning process should be developed so that one may remove surface damage in wafers, so that in later experiments to use poorer wafers, one may know the consequences of the type of surface being dealt with.

4. A range of wafers should be obtained for which the characteristics are well documented. This should include good Czochralski material (polished and as-sawn), float zone material (polished and as-sawn), polysilicon wafers, and metallurgical grade silicon wafers. A variety of known doping levels should be obtained. Then, using the results from 1 to 3, solar cells should be made and fully characterized. This will allow one to properly answer the question as to whether low quality substrates can be used. It should also provide indications as to just how high the open circuit voltage can be pushed in the heterojunction structure.

5. A detailed investigation of the tandem structure should be undertaken. This should include a diffused junction silicon solar cell as a base cell.

6. Experiments should be conducted on using screen printed silver as a contacting material to determine whether it can be used in conjunction with amorphous layers. Firing through a conductive oxide may allow this to be used. A conductive oxide process which is compatible with the amorphous layers should be developed.

7. A joint project should be considered between Carleton University and University of Western Ontario.

Specific to UWO.

In my visits to meet with the research group at the University of Western Ontario, it became obvious to me that the group were under-equipped and under-financed. They have been trying to do detailed research into a complicated process with totally inadequate resources. As an example, the LPCVD system is an in-house developed one with limited capacity. There are commercially available ones which can be simply added to diffusion furnaces. With their current finances, the group can not afford to purchase such a system, and does not even have a diffusion furnace which is suitable. I feel that the work suffers from this lack of equipment for processing, as well as from the lack of suitable characterization equipment. With this preamble, I make the following recommendations.

1. The group must seek additional financial resources to obtain suitable equipment.

2. I recommend that the group establish a wider range of contacts with Industry and with Government laboratories in order to get access to equipment, particularly for sample characterization.

3. The group should develop a processing laboratory which can be used for standard processes. This includes wet etching facilities, diffusion facilities, and screen printing facilities. Then having developed such a facility, they should develop a standard diffused junction solar cell process which can be used as the standard against which all other processes are compared. The discipline of running samples periodically through a standard controlled process will enhance the results achieved in non-standard processes.

4. A second LPCVD system must be prepared. Better yet, the group should seek funding for a commercial LPCVD system.

5. A proper solar simulator should be obtained, and measurement procedures worked out so that there is confidence in the results.

6. A program of study on the stability of the heterojunction cells should be undertaken.

7. I recommend that the group approach Prof. Tarr at Carleton University to cooperate on further work.